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A.C. circuit interruption

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A. C. CIRCUIT INTERRUPTION

BY

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THESIS

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INTRODUCTION

In the last few years the transmission voltages have increased tremendously. Along with the voltage increase came increased load carrying ability for the circuits. The first few links of a new 330 KV transmission system are now under construction in this country. Sweden is already operating a 380 KV line. It is expected to carry a load as high as 850,000 KW on a single circuit.

Interconnection between systems in adjoining areas is a practice to get further operating benefits. The benefits are - reduction of necessary reserve capacity, increased load diversity, and decreasing losses.

Both of these developments bring benefits, but they also bring problems; the major ones being those of circuit interruption. With higher voltages and larger capacities behind a system these problems become difficult. There has been much recent literature on different phases of the interruption problem but none combining all of these phases in a single discussion.

Arc Characteristics

Interruption of an electric current comprises two consecutive steps. The first consists of inserting a section of gaseous conductor into the all metallic current path. The second step is depriving this gaseous section of its current conducting ability. The two steps constitute the rapid changing of the predetermined section of a circuit from a conductor to an insulator.

Most electric circuits contain appreciable amounts of inductance; therefore a considerable quantity of energy is stored in the flux linkages associated with the flowing current. If a sudden break in the circuit should bring the current to zero almost instantaneously, the extremely rapid rate of change of flux linkages would induce tremendously high voltage across the inductive elements. In terms of conservation of energy it is obvious that the stored energy can not just disappear, but must be transformed into some other form of energy such as heat. Consequently the voltage breaks down the gap and causes a gaseous discharge current.

When a pair of cooperating contact members is separated, a progressively widening gap is formed between them. This gap constitutes a gaseous conductor of current as long as it remains in the particular condition which it acquires during the time of initial contact separation. If this gaseous conduction is a self-sustained discharge of electricity, it is known as an arc. The discharge becomes self-sustained in the following manner. The atoms of the gas are caused to become ions, or charged particles, when one or more of the satellite electrons have been removed. The ionization of an atom or molecule requires the expenditure of a definite amount of energy and may be effected in various ways. This ionization may be caused by thermal action; that is the velocity of the atoms or molecules caused by increased temperature is sufficient to cause ionization by the impact of collision of the atoms. Another method of ionization is caused by collision of atoms with charged particles which have been accelerated by an electric field. There is some emission of electrons from the solids, such as the contacts and insulating walls due to the high field.

As was previously stated the arc was initated when the contact members began to separate. The current flow continued between minute areas of surface irregularities. This current flow heats the points. Under the action of the electric field strength electrons are emitted from the cathode hot spots. These collide with neutral molecules, thereby splitting them up or ionizing them electrically. The electrons are accelerated toward the anode and the positive ions toward the cathode. By the collisions of these particles new electrons are liberated within the arc column and at the electrodes. If by this mechanism an equilibrium is established, the arc remains burning; if not, the arc extinguishes.

The correlation of voltage and current in an electric arc is entirely different from that in solid conductors; whereas, in metals the voltage is proportional to the current, the voltage between electrodes of a burning arc decreases with rising current down to a limiting value and again increases if the current is diminished. The initial breakdown of the gap between the electrodes requires a high ignition voltage at zero current. The subsequently increasing current augments rapidly the conductance of the gas so that the arc voltage gradually decreases. This deviating behavior as compared to metals is due to the different type of the transport of current in the arc. This is shown in Figure 1.

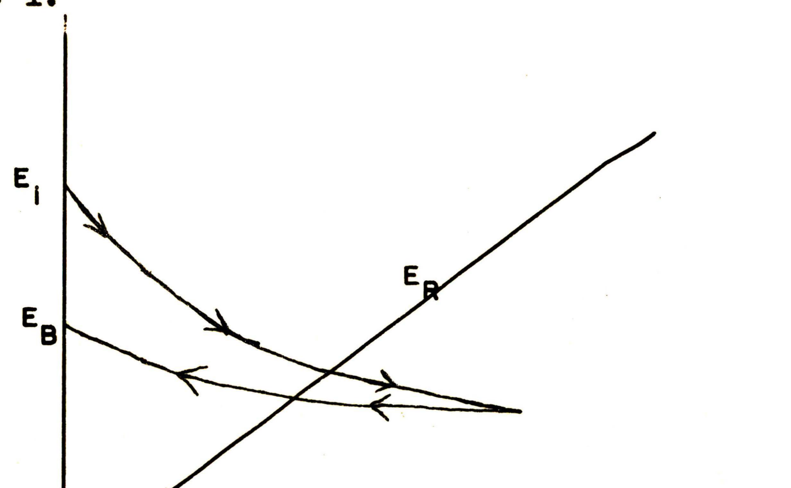


Figure 1

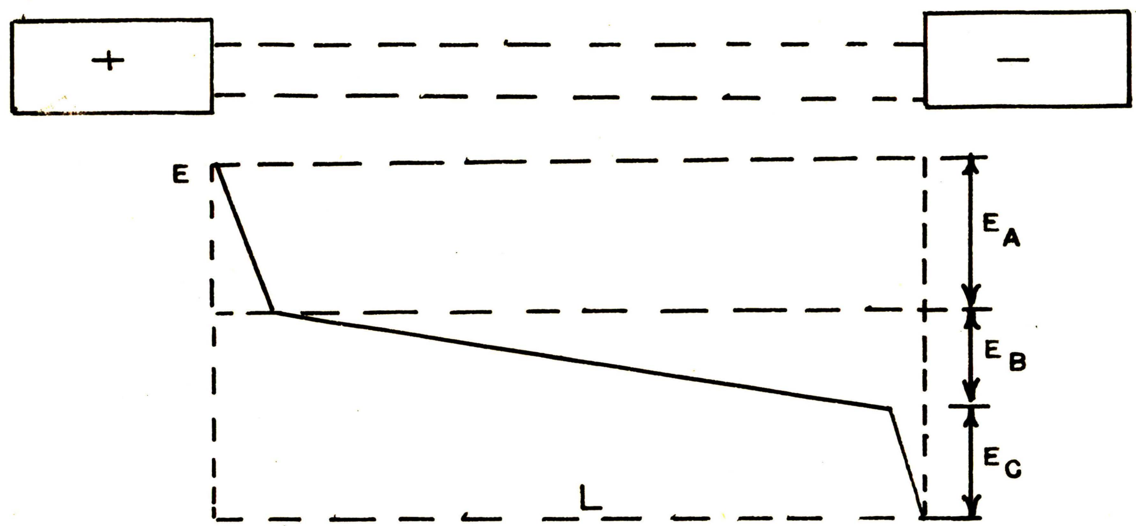
Relationship between voltage and current in arc and in conductor.

E_i = Ignition voltage

E_b = Voltage across arc

E_R = Voltage in solid conductor

The voltage drop in solid conductors is mainly determined by the current density. In an arc, however, the conductivity and even the cross sectional area change with current. The distribution of voltage between contacts is shown in Figure 2.



Arc Voltage Distribution

Figure 2

E_A = Anode drop

E = Burning

E_B = Voltage over length of arc

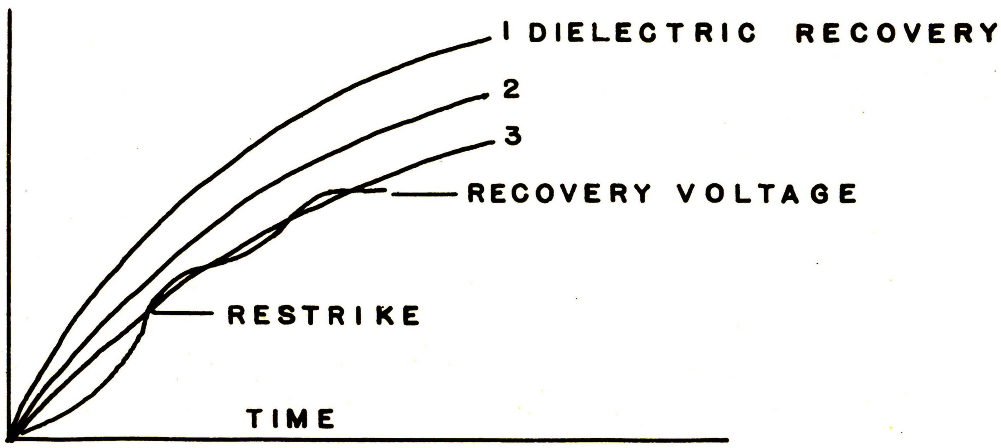
E_C = Cathode drop

It is divided into three parts; E_A the anode drop, E_B voltage over the arc length, and E_C the cathode drop. E_A and E_C depend slightly on current but E_B depends on the length of the arc.

A direct current arc will be extinguished provided that for all current values the voltage necessary to sustain the arc is greater than the available circuit voltage at the arc terminals.

The extinction of arcs in a-c circuits is fundamentally easier than in d-c circuits, because the alternating current passes regularly through zero after every half cycle. These zero instants are the ideal times for circuit interruption. The stored magnetic energy in the circuit is then also zero. Also, the power input to the arc is likewise passing through a zero value. This makes it apparent that it would be ideal to operate the switch or breaker at this current zero. Due to the extreme accuracy in timing required, this type of interrupter has not been successfully devised yet. However, all existing AC interrupters prevent the arc reigniting after a current zero. The action of an interrupter depends on two consecutive steps: (1) loss of conductance by the arc, (2) the recovery of dielectric strength by the arc space.

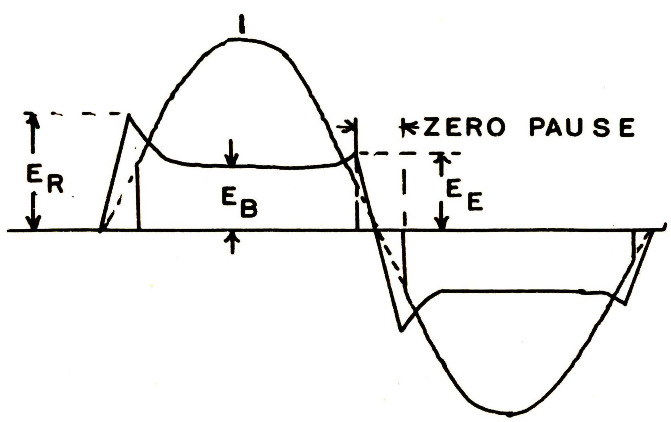
The arc path cannot regain its ultimate dielectric strength instantaneously; it takes time for the arc products to disappear and in effect heal the path. The restoration of the dielectric strength is a function of time. If the voltage across the arc path exceeds the dielectric strength of that path, the arc will restrike and a new dynamic state ensues. This is shown in Figure 3 below.



Dielectric and Voltage Recovery
Figure 3

In alternating current circuits if the arc is not extinguished at the end of a half cycle of the current wave, the arc is re-established at the beginning of the consecutive half cycle. The residue of the ionized gas tends to aid this re-establishing of the arc.

Upon reignition the arc current rises first rapidly and then more slowly in accordance with the normal wave. As the current approaches zero, but prior to the zero, the effect of deionization and cooling becomes predominant causing the arc voltage to rise above the burning voltage and forces the current to zero. During the zero pause deionization continues to take place; thus making the reignition voltage higher than the extinguishing voltage at the end of the preceding half cycle. Figure 4.



A-C Arc Current and Voltage

Figure 4

E_R = Reignition voltage

E_B = Burning voltage

E_e = Extinguishing voltage

Eventually this reignition voltage becomes permanently higher than the voltage applied across the arc space by the circuit and final interruption takes place.

The reignition strength may be artifically increased by influencing the arc principally by lengthening, cooling, and deionizing the arc column and its contacts. It is recalled also that the ignition voltage varies greatly depending on the gas pressure in the arc region. These actions are discussed more fully in their application to breakers.

Basic Circuit Interruption

The conditions with which an interrupting device must cope are dictated by the characteristics of the circuit of which the device is a part. The interrupting device not only operates during but also causes rapidly changing circuit conditions. Any electrical circuit is normally in a balanced or steady-state condition. This balanced condition exists until a change is made or occurs in the elements of the circuit or device. Whenever a change is made or occurs in the circuit, a new distribution of currents and voltage is brought about. This redistribution is accomplished in general through a transient period during which the resultant currents and voltages may momentarily be relatively high.

The voltage impressed by the circuit upon the interrupting device is termed the recovery voltage. This voltage is impressed by the circuit just after the extinction of the arc which usually occurs at a natural current zero. This voltage tends to break down the arc gap and re-establish the arc. This voltage consists of two components. The first component is the fundamental frequency or steady state voltage. The second is the transient component. This component appears immediately after the sudden change and simply adds to the fundamental frequency component. If the system is considered to have lumped constants, this transient frequency is:

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

Where L is the inductance and C the capacitance of the system.(1)

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(1) Peterson, Harold A., Transients in Power Systems, John Wiley, p. 57, 1951.

This is not absolutely true if it is considered that the transmission line actually has distributed constants. There are traveling waves on the line brought about by the changing conditions.(2)

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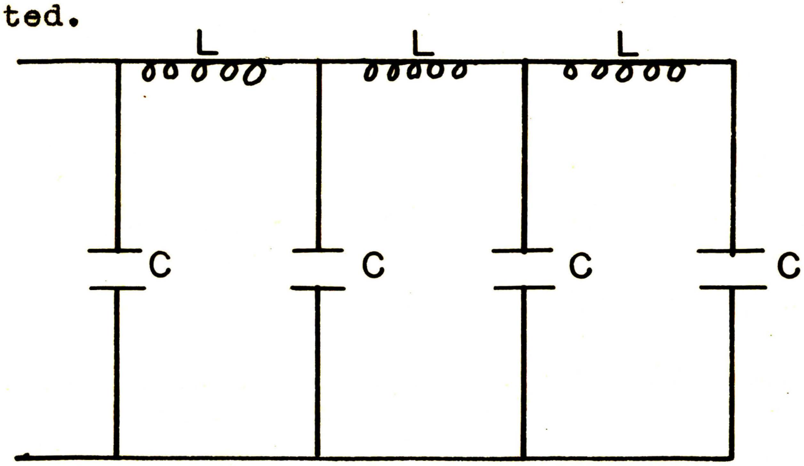
(2) Central Station Engineers of the Westinghouse Electric Corporation, Electrical Transmission and Distribution Reference Book, Chp. 15, p. 523.

A transmission line can be regarded as being made up of elements as illustrated below in Figure 5 if resistance is neglected.



Equivalent Line with Distributed Constants
Figure 5

If a change in voltage is brought about at one of the capacitors, it is charged to the instantaneous voltage; but due to the series inductance, the second capacitor is charged with a delay and so on down the line. It can be seen that the change in voltage is propagated along the line in the form of a wave. A wave of current accompanies the wave of voltage. The current wave will have the same wave form as the voltage at any instant and will be proportional to the voltage. This constant of proportionality is the surge impedance $\sqrt{\frac{L}{C}}$. The velocity of propagation of any electromagnetic disturbance is the same as light. In transmission lines the lines only act as guides. If two waves that are traveling in opposite directionson the line meet, they do not influence each other. At the meeting the instantaneous amplitudes add together, but after passing, remain unchanged. At a point of discontinuity these characteristics can be investigated. Let e_f and i_f be the forward wave of voltage and current, and e_r and i_r be the reflected waves. Then:

$$e = e_f + e_r$$

$$i = i_f + i_r$$

$$zi = e_f - e_r$$

$$i = \frac{e_f}{z} - \frac{e_r}{z}$$

$$e + zi = 2e_f$$

If the line is terminated in a resistance, r:

$$e = ri$$

$$i = \frac{2}{r + z} e_f$$

$$e = \frac{2r}{r + z} e_f$$

$$e_r = \frac{r - z}{r + z} e_f$$

With an open circuit r is equal to infinity. $e_r = e_f$ The reflected wave is equal to the oncoming wave. Therefore $e = 2 e_f$. This is the doubling up effect as the voltage wave strikes an open line end.

For short circuit, $r = 0$, $e_r = -e_f$. The reflected wave is the negative of the forward wave. Then $e = 0$. This gives $i_r = i_f$ or the doubling up effect of the current.

If $r = z$ then e_r is equal to zero, no reflected wave exists. The wave merely disappears as the end is reached. For other cases the reflected wave will be positive or negative depending upon the extent to which r is greater or less than z.[3]

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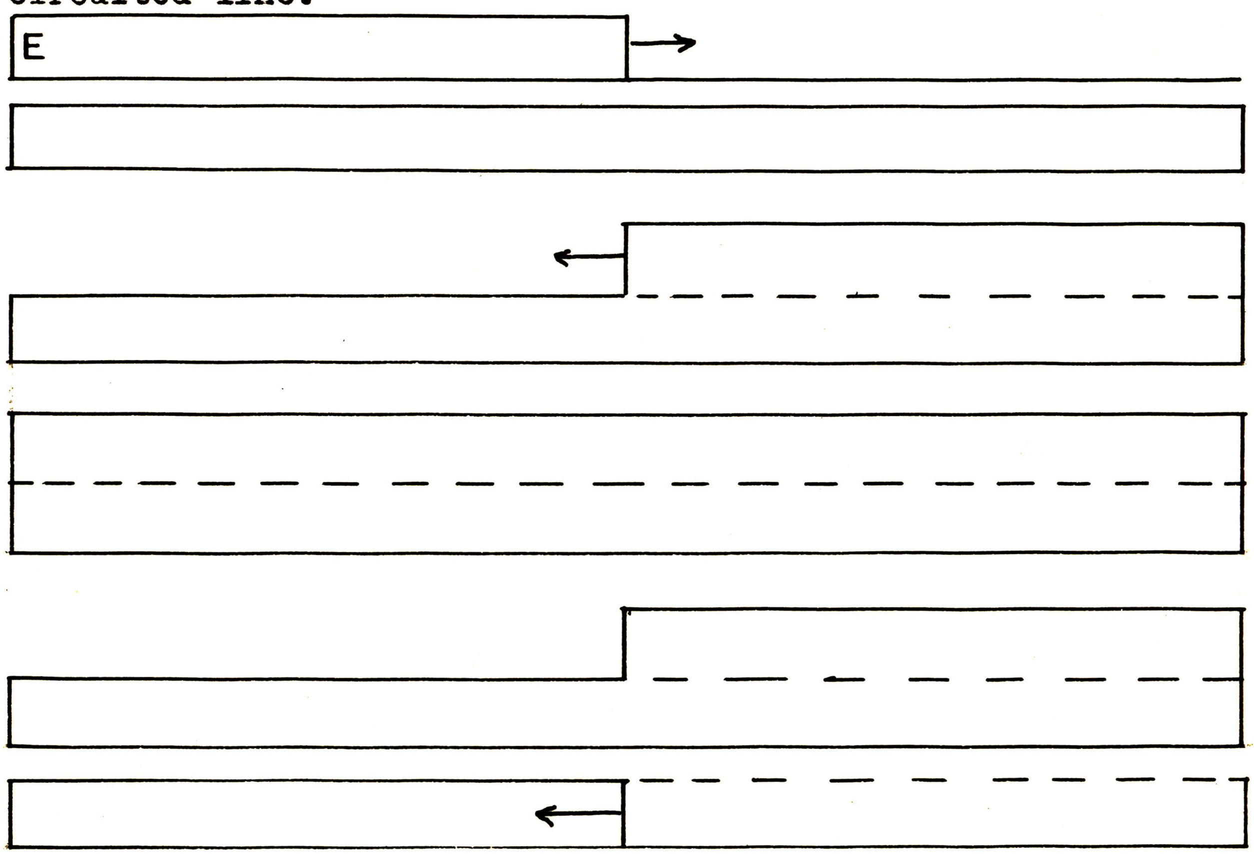
(3) Central Station Engineers of the Westinghouse Electric Corporation, Electrical Transmission and Distribution Reference Book, Westinghouse, pp. 523-527, 1950.

Consider an open line. If a step voltage is introduced at one end of the line, it travels down the line at the speed of light if the line is an open-wire line. From the previous discussion it was stated that the wave upon reaching the open end was reflected with no change in sign. Therefore, it builds up to twice the amplitude and travels back to the source where it is reflected as one times the amplitude back to open end, reflected back and reaches zero at source end. In traveling four times the length of the line it has gone through a complete cycle.

For this case the frequency period = $\frac{4L \text{ (miles)}}{186{,}000 \text{ (miles/second)}}$

$$f = \frac{186{,}000}{4L}$$

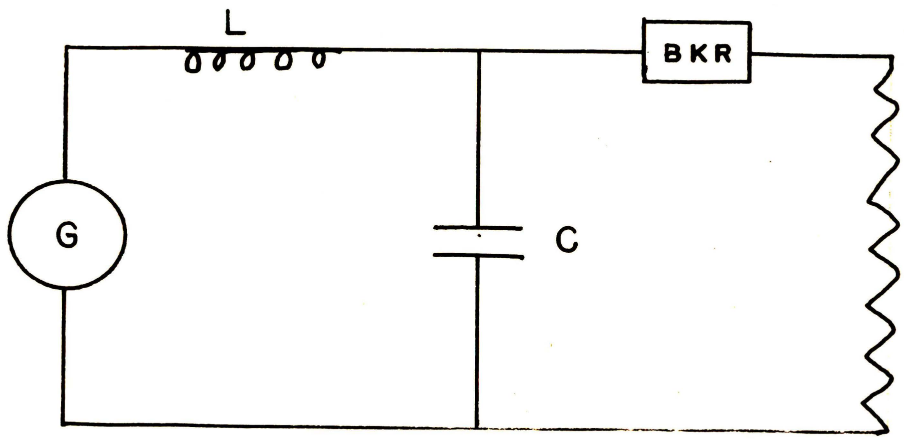
This is a very simple case. In considering a breaker opening a fault current, the line initially was terminated in a short circuit; then when the breaker operates it becomes an open line. If there is a restrike, it becomes a short circuited line.



Traveling Wave on Open Line
Figure 6

In light of these difficulties it is necessary to investigate some basic circuits.

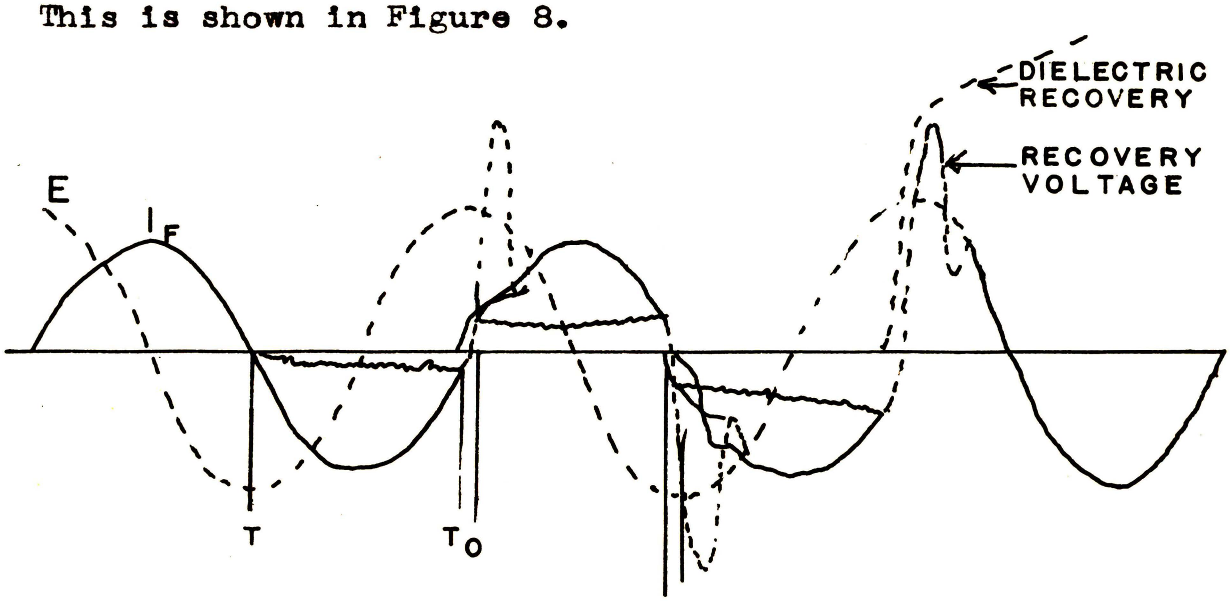
Given the basic circuit as shown in Figure 7.



Fault Beyond a Capacitor

Figure 7

Assume a short circuit exists beyond the switch. Initially the switch is closed. At that instant the voltages and current are at stead state, therefore, they are out of phase. ($e = E_g \cos wt$; $i_f = I_f \sin wt = E_g/wL \sin wt$.) This is shown in Figure 8.



Voltage & Current During Interruption

Figure 8

The circuit is interrupted at t_O when the current is zero. After the fault current is interrupted the voltage across the breaker becomes the voltage across the condenser. The capacitor was left with zero charge at arc extinction but the source has near peak voltage at this instant. This source voltage charges the condenser so that the voltage of the condenser is accelerated toward the normal voltage but due to the inductance it will overshoot. If no losses were present the voltage would reach a crest equal to twice normal. For high natural frequency and small damping the voltage reaches this maximum after a half-cycle of the natural frequency. Since in power circuits the natural frequency is in the order of 5000 through 20,000, the first peak appears such a short time after the opening of the breaker that the arc may be reignited almost immediately, but if it isn't reignited it probably will remain extinguished.

The previous discussion is shown in the following solution.(4)

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(4) Peterson, Harold A., Transients in Power Systems, John Wiley, p. 56, 1951.

At t_0 a current $-i_f$ is introduced $V_R(P) = i_f(P)Z(P)$ looking back into the circuit from the breaker.

$$Z(P) = \frac{P/C}{P^2 + \frac{1}{LC}}$$

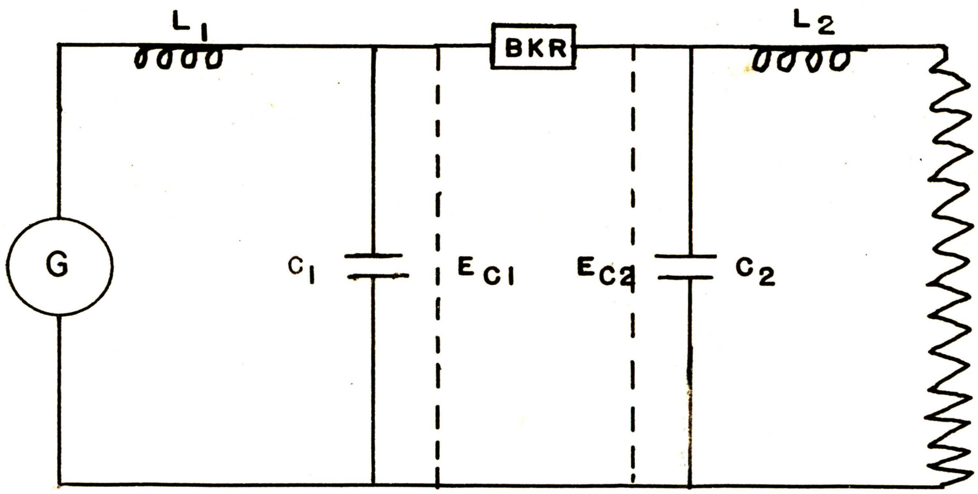
P is the operator.
L is the inductance.
C is the capacitance.

$$V_R = \frac{E_g}{1 - \frac{X_L}{X_C}}\left(\cos wt - \cos \frac{T}{\sqrt{LC}}\right)$$

$$= E_s \left(\cos wt - \cos \frac{T}{\sqrt{LC}}\right)$$

E_s is the peak value of the fundamental frequency voltage. The second term is the natural frequency term.

If the breaker is located between two parts of a circuit such as midway of a transmission line with a short circuit at the far end of the line, each part has its own natural frequency oscillation. This is illustrated in Figures 9 and 10. Figure 9 is the circuit diagram. Figure 10 is a sketch of voltage and current.



Multiple Oscillating Circuit

Figure 9

Both parts of the circuit contain inductance and capacitance. With this case upon circuit interruption, the voltage divides into two parts. The capacitances are usually so small that they do not take any considerable share of power frequency current. The voltages therefore are proportional to the inductances of the two parts of the circuit, before interruption.

$$E_1 = \frac{L_1}{L_1 + L_2} E$$

$$E_2 = \frac{L_2}{L_1 + L_2} E$$

After interruption of the circuit the two parts of the circuit oscillates at its own natural frequency. These frequencies will usually be different. The source side will oscillate at its natural frequency under its share of voltage E. The fault side will oscillate at its frequency but this will decay to zero because there is no driving voltage. This is shown in Figure 10.

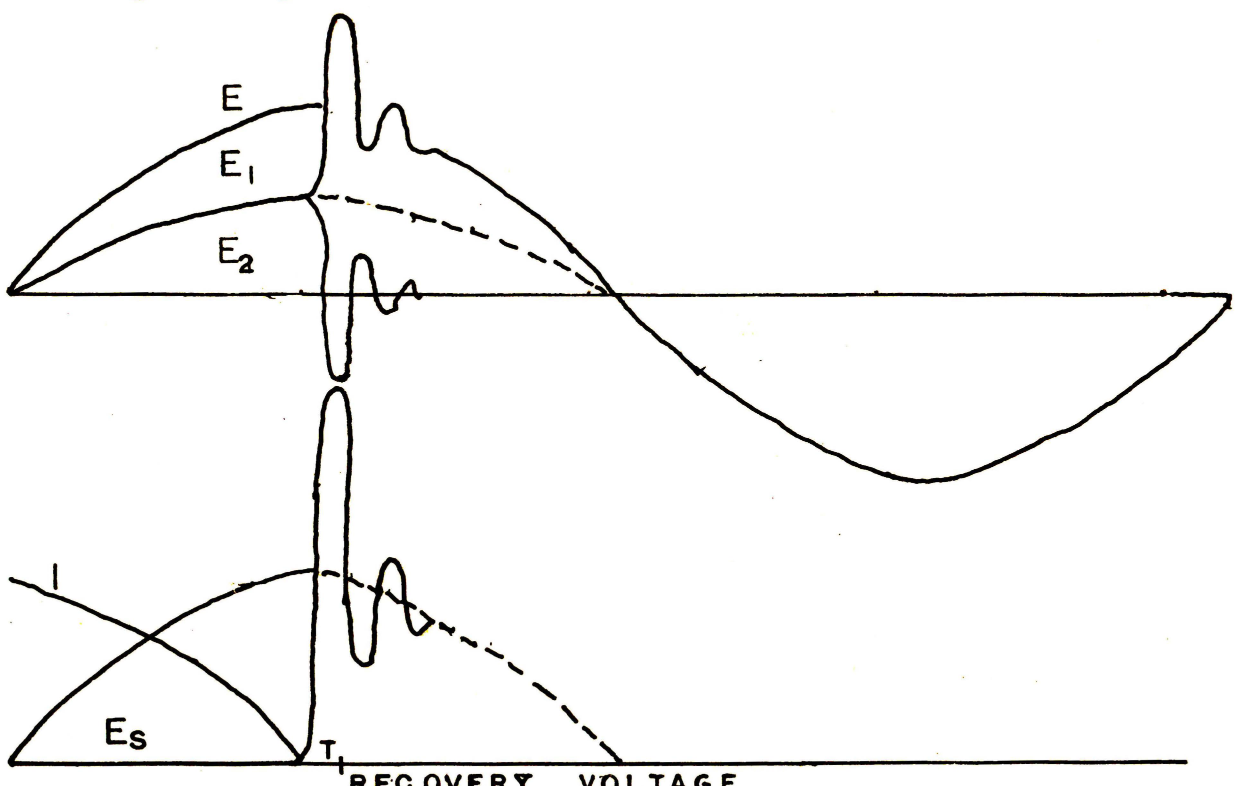


Figure 10

Referring to Figure 10, the current is interrupted at T_1. E_1 is the part of the voltage across the source side therefore the oscillations are about the source voltage. E_2 is the voltage of the fault side of the network so it will oscillate around zero because there is no source voltage. If T_1 occurs at current zero, the voltage across the breaker is never greater than 2E. Usually it is less than this because the two natural frequencies do not reach their maxima simultaneously. The transient recovery voltage of actual circuits are much more complicated since there are usually a multiplicity of oscillatory circuits included resulting in a multiplicity of natural frequencies. If the interruption is premature both the amplitudes E_1 and E_2 of the transient oscillations will be increased by a factor which depends upon the ratio of fn/w and arc quenching time constant, where, fn is the natural frequency, and w is the fundamental.[5]

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(5) Reinhold Rudenberg, Transient Performance of Electric Power Systems, McGraw-Hill, p. 542, p. 544, 1950.

Capacitive Circuits

Assume a basic circuit as shown in Figure 11 below.

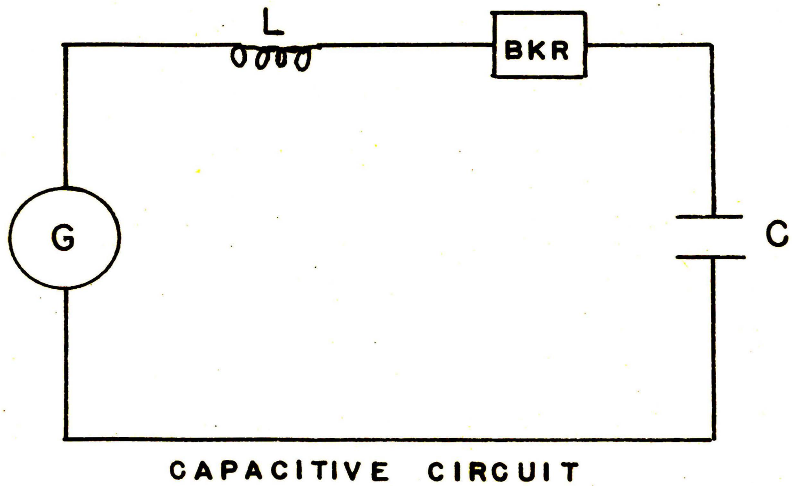


Figure 11

Figure 12 shows the recovery voltage for this circuit.

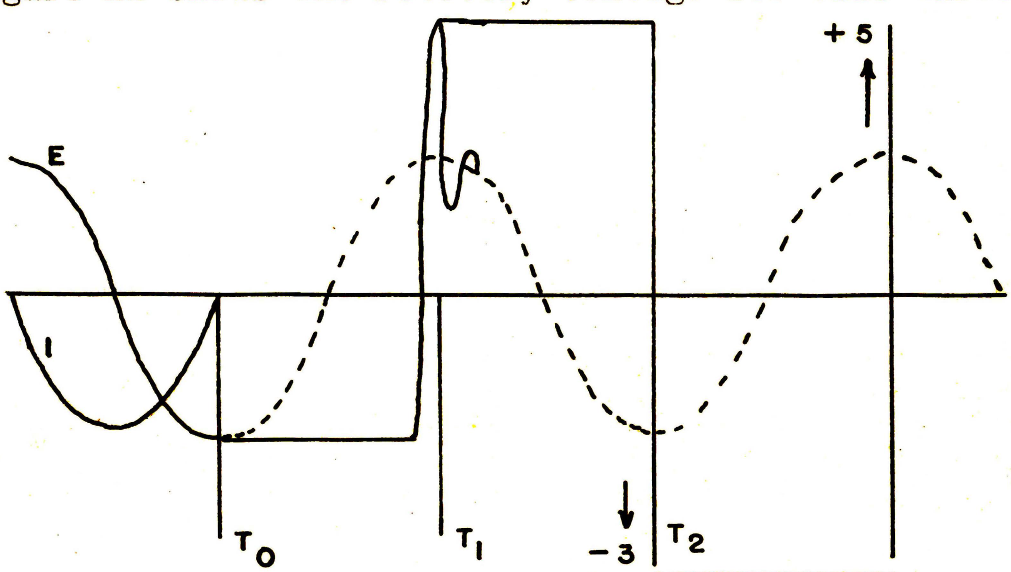


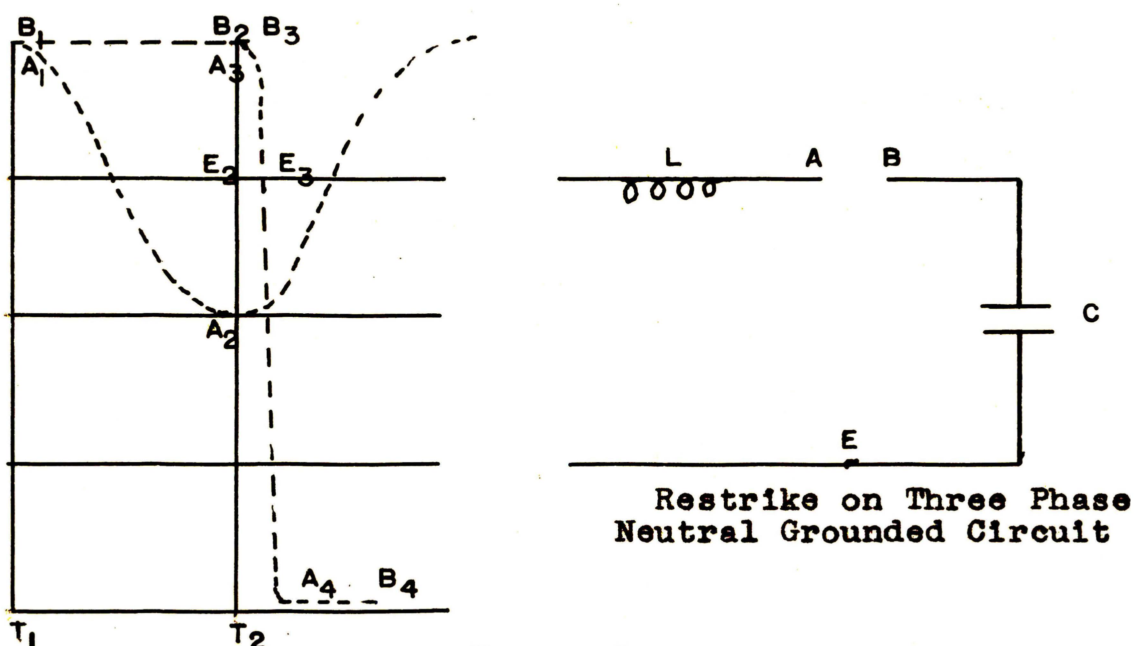
Figure 12

Initially the circuit was at steady state. If the circuit is interrupted at a current zero, the voltage across the condenser is at the maximum value. This interruption takes place at T_0. The capacitor retains the charge existing at time of interruption during the time that the arc is interrupted. The source voltage in the meantime has reversed. A recovery voltage of twice the peak value builds up in one-half power cycle. This may cause a restrike any time during the half cycle. In the most unfavorable condition the restrike occurs at time T_1.

The capacitor voltage will tend to change to the source voltage but because of the transient oscillation will over shoot and without damping will reach three times the normal value above ground. This is reached at about half-cycle of the transient frequency. This transient frequency, however, is much lower than that in the inductive circuit because of the large capacitance. If extinction occurs at this instant, T_2, the voltage remaining on the capacitor is three times the normal. Again the source voltage changes and if there is a restrike half a cycle later the voltage will over shoot to 5 times the normal value. It can be seen that if this systematic restriking continues the capacitor voltage buildup will be according to a series, 1, 3, 5, 7, etc.; the corresponding recovery voltage will have a sequence, 0, 2, 4, 6, etc.

Three Phase Interruption

If short-circuit currents are interrupted in three phase networks a number of additional phenomena occur. Figure 13 shows the condition on restrike of first phase to clear on a neutral grounded circuit.



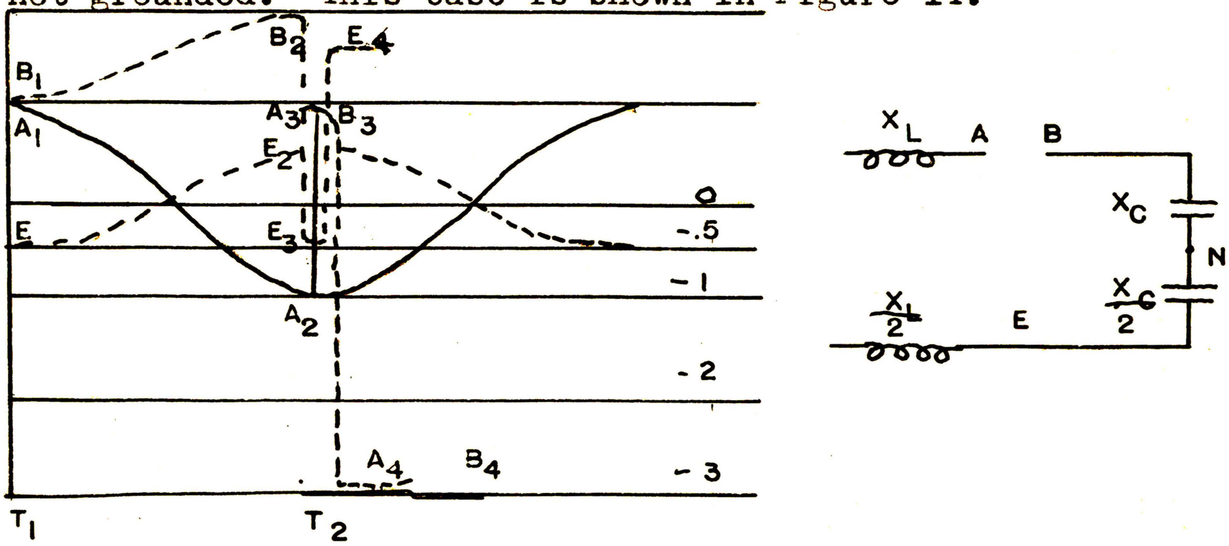
Restrike on Three Phase
Neutral Grounded Circuit

Figure 13

Referring to Figure 13, the points A and B represent the contacts of the breaker, C the capacitor load, and L the inductance of the system. E represents the grounded neutral. The points 1, 2, 3, 4 show the voltages of the different points at time of arc extinction, just prior to restrike, at restrike, and immediately after restrike, respectively.

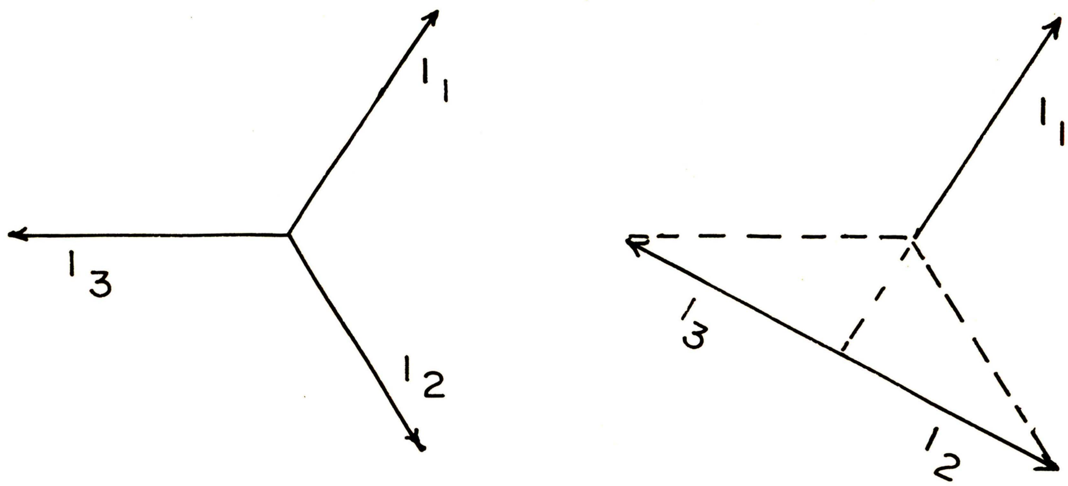
The arc of the first phase to interrupt is extinguished at T_1. At that time the capacitor is charged to the normal peak value which it retains until a restrike occurs. The source voltage in the meantime has changed to its negative peak value. The voltage across the breaker is twice normal peak and probably a restrike will occur at T_2. The capacitor charges toward the source value but over shoots to a negative three times normal. The voltage of point e has remained at zero because of the grounded neutral. This condition gives a maximum voltage on the breaker of three times normal.

The condition is somewhat different if the neutral is not grounded. This case is shown in Figure 14.



RESTRIKE ON THREE PHASE NEUTRAL NOT GROUNDED
Figure 14

In three phase circuits with the neutral not grounded, one current is interrupted one-hundred and twenty electrical degrees ahead of the normal zero of the other phase. This current being zero from that time on during interruption forces one of the other phases to act as the return for the other. This is shown in Figure 15.



Vector Diagram of Currents
Figure 15

This causes the magnitudes to change. The first phase current changes to 3/2 its value while the other two change to $\sqrt{3/2}$ its original value. The other two phases reach zero simultaneously. This is used in Figure 14, showing that the neutral point is located Xc/2 away from c and XL/2 from source. At T_1 the first phase is interrupted. The capacitor Xc is charged to maximum voltage and retains this charge but the neutral point has changed to include Xc/2 so that the voltage of point b is 1.5 normal just prior to restrike. The source voltage reverses and reaches its negative peak at T_2. If a restrike occurs at T_2 both capacitors Xc and Xc/2 are charged. Xc will reach a voltage negative three times normal above ground.

Comparison of American and European Breaker Ratings

Recently there has been a considerable exchanging of breakers between America and European countries. This led to the necessity of comparison of the ratings. The European breakers are rated in accordance to the International Standards while the American breakers are rated by the American Standards. There are some outstanding differences between the two systems.

A fair comparison of American breakers with breakers of European make, which are nearly always rated on a symmetrical basis, is almost impossible. It is frequently claimed that a European breaker rated, for instance, 5,000 MVA is equivalent of a 7,500 MVA breaker rated according to American Standards. Generally, the European breaker is tested at 5,000 MVA with symmetrical current and at 7,500 MVA with highly asymmetrical current. The American breaker may have been tested at 7,500 MVA with both symmetrical and asymmetrical currents. Yet a 3-cycle breaker, without exceeding its rating could not be used in any network whose symmetrical short circuit duty exceeded 7,500/1.2 = 6,250 MVA or 7,500/1.6 = 4,700 MVA if the breaker were required to interrupt the initial short circuit current as stipulated.

If the American breaker were really tested with 7,500 symmetrical MVA, it is probably capable of successfully interrupting higher asymmetrical MVA. See tables I and II in the Appendix.(6)

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(6) St. Clair, H. P., and Naef, Otto, Consideration In the Rating and Testing of Power Circuit Breakers, A.I.E.E. 52-29, December, 1951.

Voltages the Insulation Must Withstand

The breakers of a given class must be able to withstand a test voltage to insure that the primary insulation is sufficient for the service. No fixed ratio exists between the voltage to which American and European breakers are tested. A listing of rated and test voltages of American and British breakers is given in table III. At voltages up to 14.4 KV the insulation tests of the American breaker are relatively much higher. At voltages of 23 through 138 KV the American test voltages are 4% or more above that of the British test. At 161 and 230 KV the American test voltages are about 2% below that of the British. The American breakers for 230 KV service are available with the same interrupting rating but with lower insulation levels. These are used extensively because experience has shown that for effectively grounded systems there is substantial savings without loss of protection.

Contact Temperature at Rated Current

Contact temperature is an indication of the cross section, the voltage drop across the contacts, and effectiveness of cooling. The American ratings are based on 60 cycle current and the temperature rise must not be greater than 30 degrees C. The British ratings are based on 50 cycle current and the permissible rise increases in steps to 50 degrees. Only breakers of 200 amperes or less are limited to a 30 degree rise. The temperature rises are given in table IV.

Experience indicates that the temperature rise is less than proportional to the current square. If it is assumed to be proportional an American 600 ampere-30 degree rise breaker could be rated 700 amperes-40 degree rise and a 1200 ampere-30 degree rise breaker could be rated at 1560 amperes-50 degree rise. Conversely, a breaker rated at 1200 ampere-50 degree rise could be rated only 930 ampere-30 degree rise.

American circuit breakers are built for operation in an ambient temperature up to 40 degrees C and some with special contacts operate at an ambient of 55 degrees. The British breakers have an average ambient temperature of 35 degrees over a 24 hour period with a peak not over 40 degrees.

Short Circuit Closing Current

The short circuit currents which the breaker is required to open and close on may be many times the rated current and may cause stresses to the apparatus. One of these forces is the electro-magnetic force on the conducting path. This force changes the contact pressures. It is necessary to limit the short circuit current to avoid the necessity of dissipating the excess energy for closing on this current.

The British breakers are listed for symmetrical breaking currents not exceeding 40,000 amperes and making currents not exceeding 100,000 peak, or an equivalent rms value of 61,000. The electro-magnetic forces at these currents are moderate and the breakers are required to close and even latch when they occur. In British Standards a factor 2.55 is used to obtain rated peak making currents from rated symmetrical capacity. This is equivalent to 1.5 for rms values.

In American systems it is common for the generators to be located with little impedance between them. This gives rise to high short circuit currents. To meet this condition breakers with short circuit ratings up to 2,500 MVA are available at voltages as low as 14.4 KV. These heavier currents require excessive closing energy if they are to be capable of latching at the higher currents. This can be reduced if the breaker is tripped immediately when it is closed against a heavy fault current. Therefore, the American breakers have two ratings for closing ability, one is a rated making current. This is the maximum short circuit current which the breaker must close with no time delay. By NEMA standards it is equal to 1.6 times the maximum interrupting current at reduced voltage. The other is the rated latching current. This is the maximum short circuit current against which the breaker must close and latch. By NEMA standards it is equal to both the maximum interrupting currents at reduced voltage and the 4 second rating. By American standards a factor of 1.6 is used as ratio between closing and symmetrical currents. Table V (see Appendix) lists comparable breakers.

Short Circuit Currents

Short circuit currents to be carried: The American breakers have two values which define their current carrying ability, the 4 second current and the rated momentary current. The first is numerically equal to the rated maximum interrupting current at reduced voltage. The second is 1.6 times this value. This value corresponds to the maximum initial value of the transient current which could equal the rated interrupting current at the time of contact separation.

The British Standards specify short time ratings for times of 1 or 5 seconds. The 1 second rating shall not be less than the rated symmetrical breaking capacity. No specification is given for the 5 second rating. See table VI in Appendix.

Interruption Short Circuit Current

The American definition of the interrupting rating is the highest rms current at a specified operating voltage which the breaker shall be required to interrupt under the operating duty specified with normal frequency recovery voltage equal to the specified operating voltage. The current is the rms value including the d-c component, at the instant of contact separation as determined from the envelop of the current wave. From this definition it is clear that the breaker may be applied up to its rated current either where no asymmetry can exist at contact separation or where asymmetry can still exist at the time of separation. ASA C-37.9-1.25 states: "SYMMETRICAL AND ASYMMETRICAL. Since both displaced and symmetrical current waves occur in practice, circuit breakers should be capable of handling their maximum short circuit current ratings with either type of wave. Laboratory testing practice is to use both asymmetrical and symmetrical currents."

The amount of asymmetry remaining at the time of contact separation depends on the initial asymmetry and the rates of decrease of the a-c and d-c components of the current. The a-c component may not decrease at all if the fault current is limited entirely by impedances of transmission lines, transformers and reactors. It may decrease rapidly if the fault current is limited principally by the impedances of generators. The d-c component, if present, always decreases at a rate determined by the ratio of the resistance and inductance of the circuit as indicated by table VII.

American methods of applying circuit breakers are based on studies of typical circuits which led to relatively simple application factors for approximating the highest probable current at various contact parting times. These are used in most usual cases but more rigorous methods are used for unusual applications. The factors define a typical short circuit current in terms of its rms value as related to the value of short circuit current obtained by calculation. This is the initial a-c component of short circuit current which would flow with the system operating under no-load conditions and equals the rated voltage divided by the equivalent sub-transient impedance determining the short circuit current and a phase constant. Factors for the general cases are given in table VIII.

With the exception of the highest speed breakers, the relay time plus breaker opening time will be equal to 4 or more cycles. These factors show that a breaker opening its contacts 4 cycles or more after the start of the short circuit may have to interrupt currents with an rms value equal to the initial a-c component determined for the system. They also show that the momentary or making current which is measured at about 1/2 cycle after the start of the current may be 1.6 times the current at parting. American breakers have their rated momentary and rated making currents 1.6 times the rated maximum interrupting currents to meet these conditions. Only breakers opening their contacts in less than 4 cycles after the circuit starts can be applied where they are required to interrupt an asymmetrical current greater than the initial value of the a-c component. The additional amount is 10% for 5 cycle breakers and 20% for 3 cycle breakers.

If the short circuit exceeds 500 MVA and when the current is supplied directly from generators or through current limiting reactors only, the d-c component may decrease very slowly and the assumed probable currents are higher than for the general case. These are given in table IX in the Appendix. These conditions would cause the largest amounts of asymmetrical currents. Breakers for these applications probably will not part contacts in less than 4 cycles.

The British breaker has two ratings to define its interrupting capacity, one for its asymmetrical interrupting current and one for the symmetrical interrupting current, with less than 20% asymmetry. The measurement of these currents agrees with American practice.

A comparison of the interrupting ratings under the two standards depends on the relative values assigned to the two British ratings. If these two British values are equal and equal to an American rating the breakers have identical interrupting ratings and can be applied interchangeably, except for a possible derating factor of .94

caused by the lower British making current.

The British usually assign an assymmetrical interrupting rating about 25% greater than the symmetrical interrupting rating. The full 25% can be used only when relay time plus breaker time is about 2 cycles and becomes zero for 4 cycles or more. In most cases contacts will not part until at least 4 cycles. This rating can be used in applications only when appreciable asymmetry exists at the time of contact parting because the a-c component must not exceed the symmetrical interrupting rating and the current at the first peak must not exceed the rated making current. It appears that the increase in rating for asymmetrical currents is not useable in at least the majority of applications. However, the breaker with higher asymmetrical rating has an advantage if it can be operated so quickly that the current at contact parting exceeds both the initial symmetrical current and also the interrupting rating of the corresponding American breaker.

A breaker made under American Standards and a breaker made under British Standards for the same voltage, rated normal current and rated interrupting capacity meet different specifications. The American breaker must be able to withstand a higher insulation test voltage, to operate at a higher average ambient temperature to carry rated normal current with less temperature rise on the contacts, to close against higher short circuit currents, to carry higher short circuit currents four times as long and to interrupt symmetrical and asymmetrical currents up to rated interrupting current equal to the rated symmetrical interrupting current of the British breaker.

Solutions Used by Industry

The necessary conditions for circuit interruption have been previously discussed. The way these conditions are brought about depends upon the solution which the manufacturing concern uses. Only a few of these will be discussed.

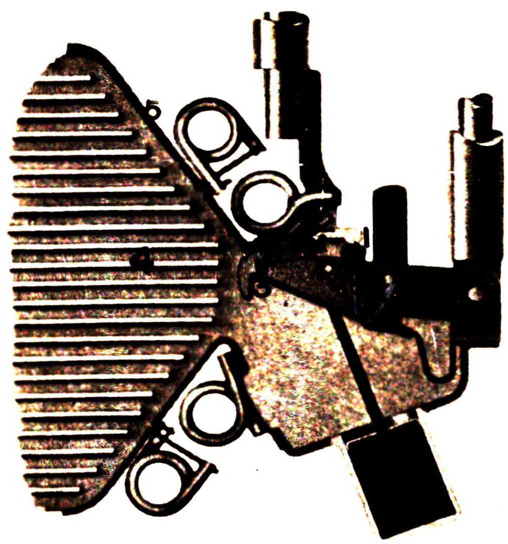
Magnetic Blast

The magnetic blast principle is one of the oldest methods used for low voltage circuits. Recently this principle has been applied to the high voltage circuits.

With the magnetic blast application the arc is drawn across a magnetic field. This field is set up by the current to be interrupted by allowing the current to flow through coils around which the magnetic field is set up. This magnetic field reacts with the arc tending to force the arc out of the field. The force is proportional to the field strength and the current of the arc, therefore, it varies as the square of the current so that for greater currents there is a greater force tending to distort the arc path. This is necessary to interrupt different values of current. The action of the field is to lengthen the arc making a higher voltage necessary to maintain the arc. To increase this action a special chamber is placed in the arc path. This chamber consists of insulating barriers around which the arc must pass. This cools as well as lengthens the arc. By this action the electrical resistance in the arc path is greatly increased which reduces both current and phase angle.

At an early zero the arc path is so long, the voltage so reduced, and the gasses produced by the arc are so cooled that the arc cannot re-establish.

An example of this type of breaker is the G. E. Magne-Blast Breaker shown in Figure 16.



G. E. Magne-Blast Breaker

1. Main Contacts
2. Intermediate Contacts
3. Arcing Contacts
4. Arc Chute
5. Arc Runner

Figure 16

The principal parts of the magne-blast breaker are shown in Figure 16. There are three sets of contacts: primary (1), intermediate (2), and arcing (3). The main contacts are silver. Upon opening, the primary contacts part first, shunting the current through the intermediate contacts without arcing at the main contacts. The intermediate contacts are made of elkonite, a special arc resistant material. These contacts part next, shunting the current through the arcing contacts and blowout coil. The intermediate contacts interrupt the current which results from the voltage drop across the blowout coils and relieves the primary contacts from interrupting any current. Because the blowout is energized before the arcing contacts part there is a strong magnetic field to force the arc into the arc chute (4). As the arc is drawn along the arc runner (5), additional blowout coils are inserted in series. Therefore, for longer arcs a stronger magnetic field is set up to force it deeper into the chute. In this breaker the arc chute is composed of zirconium powder and asbestos together with a binder. The chute consists of gradually interleafing fins of the insulation material. It can be seen that the deeper the arc is forced into this chute the more it increases in length.

This type of breaker is built for voltages up to 15 KV and 500,000 KVA. As was previously stated, this type of breaker has just recently been used for high voltage applications.

Oil Breakers Plain Break

Oil has been used for many years not only as improved insulation compared to air, but also for greater effectiveness in arc extinction.

By immersing the contacts in oil or other liquids, the production of an arc during their separation cannot be prevented. However, the oil cools the arc column and the contacts so intensely and also causes an increase in pressure that for the same arc length a considerably higher voltage develops than with discharge in air. The extinction voltage can be raised to a high multiple of the corresponding voltage in air by embedding the arc in oil. Therefore, oil breakers are particularly suited to high voltage circuits.

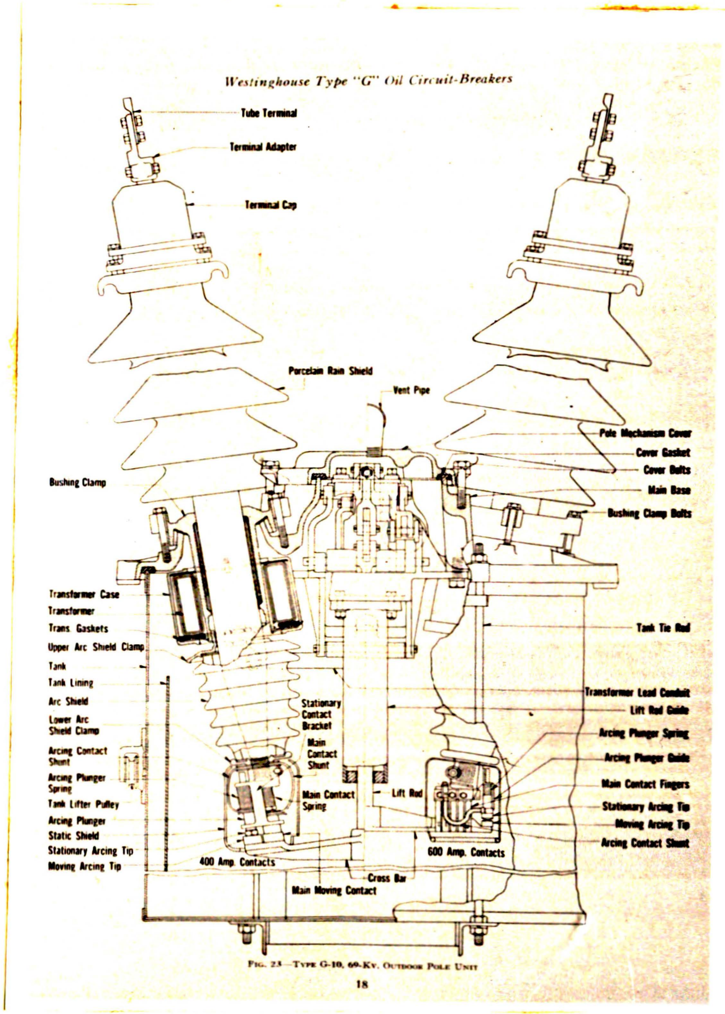
As the contacts separate an arc is initiated. This arc decomposes the oil due to the high temperature. With this decomposition gas is formed, surrounding the arc. This body of gas is spoken of as the gas bubble. The bubble has several essential parts - core, envelope, vapor zone, and a zone of saturated vapor. The core of the arc extends between the contacts and has a temperature in the order of thousands of degrees absolute. The envelope which surrounds the core has a temperature in the order of hundreds of degrees. The envelope is surrounded by a zone of superheated vapor. Zone three is surrounded by another zone of saturated vapor. The total amount of vapors and gases evolved by the arc depends upon and increases in proportion to arc energy. The most important gas in the bubble is hydrogen.

As a general rule, the speed at which a gas diffuses increases in inverse ratio to the density of the gas. Any gas having a tendency to diffuse rapidly should also have a tendency to rapidly transfer heat by conduction. The thermal conductivity of hydrogen is high resulting in high rates of heat flow and rapid cooling.

The vapor generated at the bubble wall flows into the arc. This vapor is relatively cool and its flow turbulent. By this method it deionizes the arc.

With transmission of the high gas pressure to the surrounding oil, the bubble expands and moves the oil outward toward the surface of the oil. The pressure reduces and becomes less than the external pressure on the oil. The bubble is compressed and the internal pressure increases again. As these oscillations in gas pressure take place, pressure peaks develop in the bubble. The frequency of these oscillations are determined by the inertia mass of oil in the breaker and size of bubble. The frequency is high in comparison to power frequency. These pressure impacts cause high voltages in the arc. Therefore, they tend to inhibit reignition of the arc.

An example of this type of breaker is the Westinghouse Oil Breaker. This breaker is shown in Figure 17.



Plain Break Oil Breaker

Figure 17

In this breaker there are two sets of contacts, main and arcing contacts. The main contacts are held together under spring tension until tripped. They separate before the arcing contacts. This reduces undue burning of the main contacts.

This type of breaker is rather obsolete due to the large amount of oil and space required and to its inability to meet modern demands except in some small breakers for distribution reclosers. This breaker is built for 23 KV and 250,000 KVA rating.

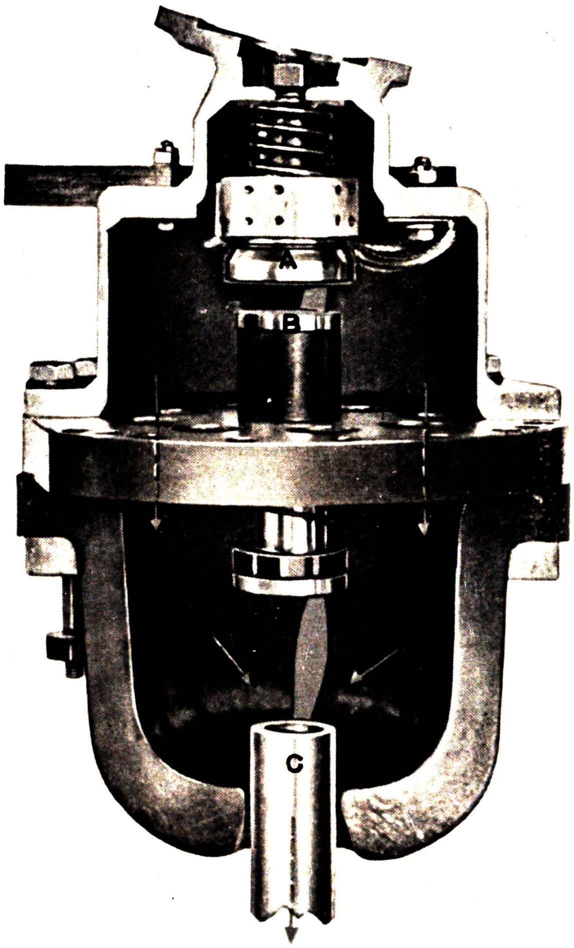
Oil Blast Principle

The characteristics of the plain break oil breaker have already been discussed. There are several undesirable conditions which should be eliminated. A few of these are as follows: an unconfined arc in oil is extremely erratic in length, duration, and amount of gas formed. The gas bubble upon which the action of the breaker depends is a rather poor insulator.

In the oil blast breaker the arc is confined in a special arc chamber. The arc breaks down the oil into gas and places the oil under pressure. The pressure may be used in one of two ways. It may force oil to follow a moving contact out through the throat of the chamber thus placing a solid wall of oil in the arc path, or there may be two breaks one to generate the gas pressure and another main break. The pressure forces the oil through channels into the main break. The latter is the more common application.

This principle is used in many of the modern breakers. Several examples are as follows.

G. E. Oil Blast Breaker shown in Figure 18.



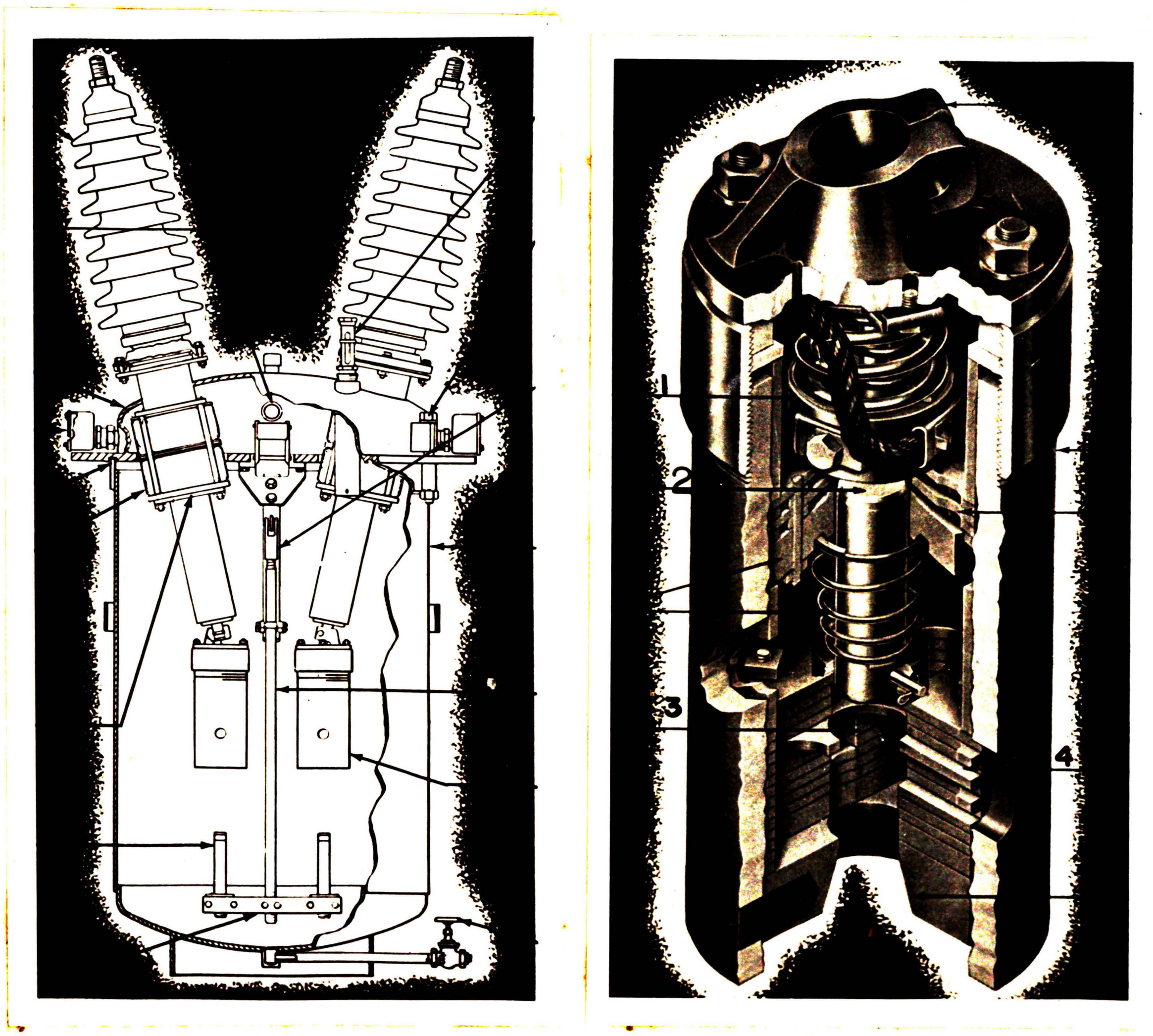
Oil Blast Breaker (Chamber)

Figure 18

The explosion chamber contains an upper butt contact A, a floating contact B, and a hollow contact C. When the breaker is tripped, the floating and hollow contacts, B and C, start down, driven by the opening springs, thus drawing an arc between A and B. The arc breaks down the oil and forms gas which places the oil in the explosion chamber under considerable pressure. When the floating contact reaches the end of its travel, the second break is formed between B and C and the main arc is drawn. The oil is forced through openings into the main arc. At a current zero the arc products are displaced by solid oil. There insulation is introduced at an extremely high rate.

This breaker is built for voltages up to 140 KV and 1,500,000 KVA.

A further development and refinement of the blast chamber is shown in Figure 19.



G. E. Cross-blast Breaker

1. Upper Contact
2. Primary or Pressure Gap
3. Secondary or Interrupting Gap
4. Baffles

Figure 19

The action of this breaker is almost identical to the oil blast which was previously discussed with the exception that the blast of oil is directed across the arc by passages in the fiber baffle stack. This increases turbulence in the arc area; thus creates greater cooling effect on the arc. The arc is also forced into baffle slots where it is lengthened.

The rating of this breaker is 69 KV at 2,500,000 KVA.

Another example of the oil blast breaker is the Westinghouse Multi-flow Breaker shown in Figure 20 on the next page. The multi-flow Deion unit consists of an upper pressure developing chamber and a lower chamber in which the arc is interrupted. The upper chamber houses the stationary contact element (1) and contains check and safety valves. The lower section consists of a stack of punched fiber plates (2) and the intermediate contact element resistors are added if necessary.

To start interruption the moving contact (3) starts downward. The intermediate contact follows the moving contact due to the intermediate contact spring. The intermediate contact leaves the stationary contact (1). An arc is formed between the two contacts; consequently, high gas pressure is built up in the upper chamber. As the moving contact (3) continues on its travel, the intermediate contact reaches the end of its travel; therefore, another gap is formed and the main arc (42) is initiated.

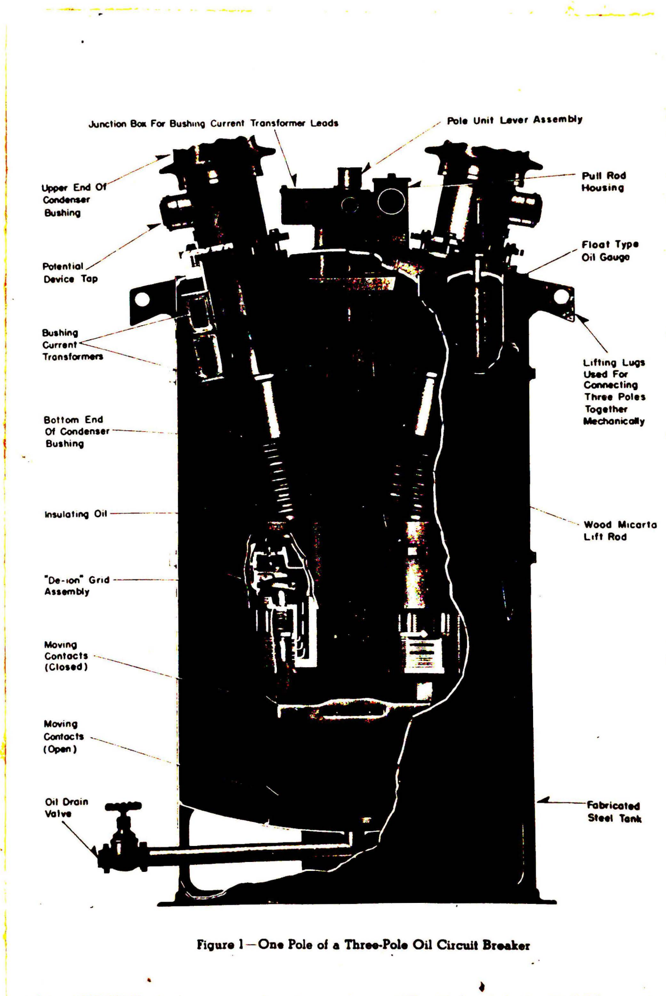
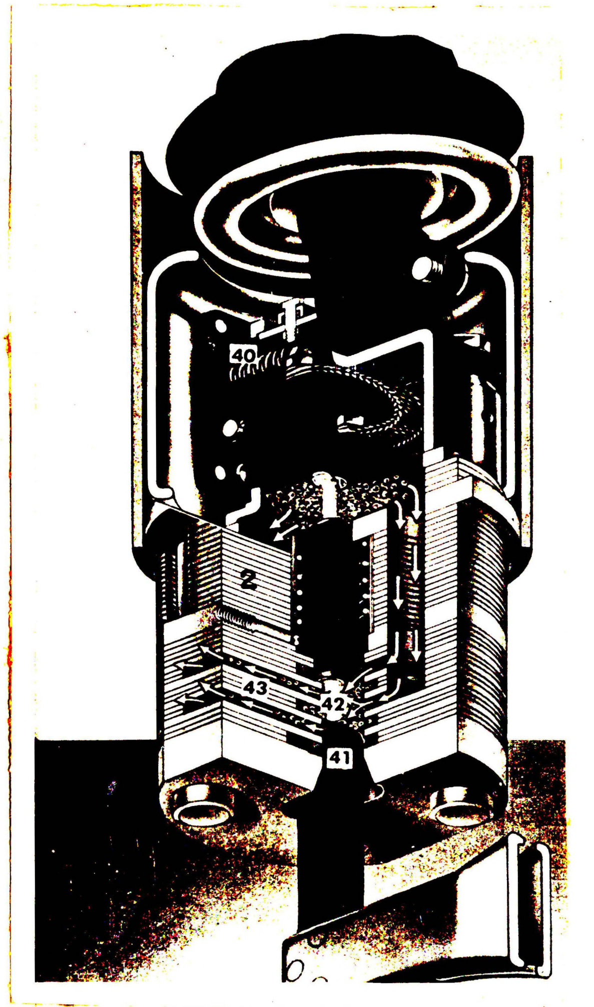


Figure 1—One Pole of a Three-Pole Oil Circuit Breaker



Multi-flow Oil Breaker

1. Stationary Contact   3. Moving Contact

2. Fiber Plates   4. Intermediate Contact

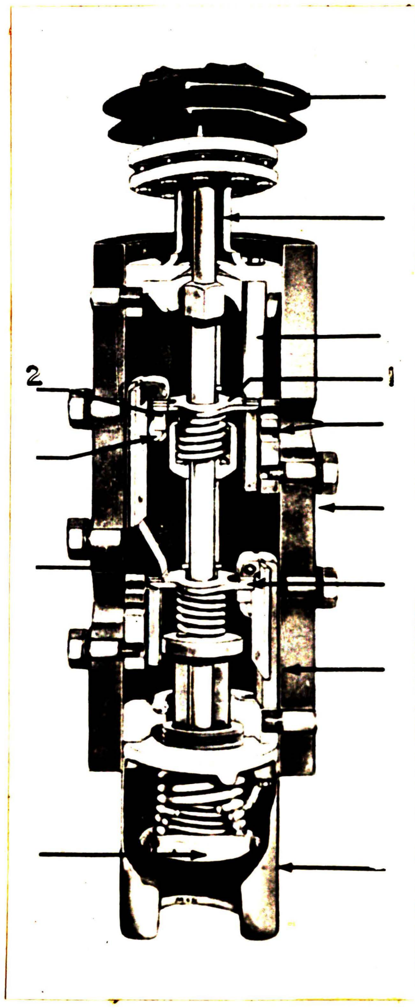
Figure 20

The pressure in the upper chamber forces a high velocity stream of oil through the passages in the grid and across the main arc. As the oil enters the arc region it travels both upward and downward because the outlets are staggered vertically with respect to the inlets and to increase the turbulence the outlets are located 90 degrees around the grid from the inlets. The oil and arc products pass out of the grid through vents in the structure. The check valve in the upper chamber allows oil to refill the chamber but automatically closes as pressure is built up. The safety valve is for protection against excessive pressure.

This type of breaker is built for voltages up to 315 KV and 15,000,000 KVA ratings.

An example of the oil blast principle extended to include multiple breaks is the G. E. Multi-break Interrupter shown in Figure 21 on the next page. The multi-break interrupter uses the oil blast principle. As the name implies, there are a series of breaks in this interrupter. The number of breaks is determined by the voltage rating of the breaker. 115-161 KV have four breaks while the 230 KV breakers have six. In the four-break interrupter, there is a pair of two-break interrupters in series. At each bridging contact (1) one break is provided primarily to create oil pressure. The second break is located so that the main arc drawn there (2) is directly in the path of a blast of oil caused by the pressure generated at the first break. There are ports located near the contacts to control the pressure.

These breakers are built for voltages up to 230 KV and 5,000,000 KVA.



Multi-break Chamber

Figure 21

Magnetic Deion Grid

The magnetic deion device differs from the deion grid previously mentioned in its operation in that the arc is drawn magnetically against the oil as opposed to the oil stream being forced across the arc path. The grid is made up of alternate plates or groups of plates made of fiber materials and good magnetic iron plates. These plates are so shaped as to provide, within the grid, a series of pockets to retain oil in close contact with the arc. On contact separation the arc is drawn in a narrow groove through which the moving contact travels. When an arc is drawn, a strong magnetic field is set up in the iron elements. This field causes the arc to be drawn against the oil while the gas generated escapes through the arc. As the arc is drawn toward the closed end of the plate slots, the high turbulence set up by the gas tends to increase de-ionization. The arc is also lengthened by alternate forces. The magnetic force tends to pull the arc into the slot while the gas blast forces away from the closed end.

An example of the magnetic deion grid is the Westinghouse Deion Grid shown in Figure 22 on the next page.

The moving contact (1) travels through a slot in the stack of alternate iron and insulating plates. When the moving contact moves down, there is an arc drawn between this and the stationary contact (2). The insulated horseshoe-shaped plates create a low reluctance field path toward the rear of the slot which causes the arc to move to the rear of the slot. The arc comes in contact with fresh oil trapped in vented pockets. This generates relatively cool and unionized gas. The resulting turbulence mixes the conducting ionized gases with the cool unionized gas. The dielectric strength is built up so rapidly at a current zero that the current remains at zero.

Magnetic Deion Grid

Figure 22

This breaker is built for 69 KV and 2,500,000 KVA rating.

Oil Poor Breakers

Even though the demand for oil reduction usually follows an electrical breakdown where ignition of oil from a circuit breaker tank has added to the effects of the breakdown, the low oil content breakers also have features quite different from lessening of fire risk.

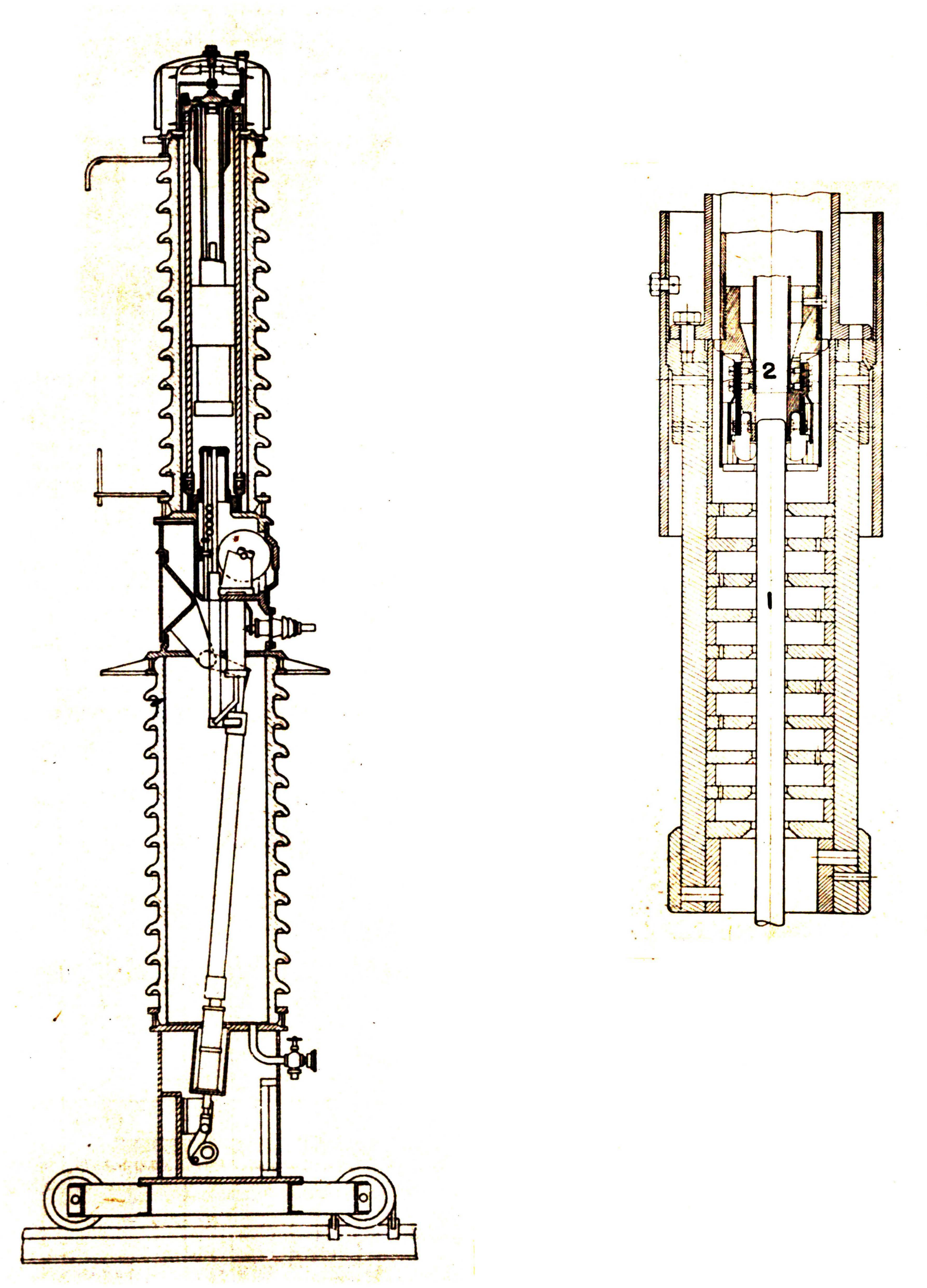
To reduce the oil content means to reduce the size of the breakers for higher voltages. There are many types of low oil content breakers. They have interrupters quite similar to a normal oil breaker but instead of being housed in a large steel tank, they are housed in a small insulating, usually porcelain, container. This type of breaker does not depend upon the gas pressure generated by the arc but rather uses a stream of oil to lengthen the arc and cool the arc column and contacts.

As the contacts part an arc is established. At this instant some control causes a piston to force a high pressure stream of oil across the arc forcing it against arrangements of arc splitters which causes interruption of the arc.

An example of this type of breaker is one manufactured by Orelikon Engineering Company illustrated in Figure 23 on the next page.

The interrupter is located in the upper of two insulating columns. The lower is used as an insulating base and contains an insulated operating rod.

The upper contact is located in the end of a 12" arcing chamber. The contact is a tulip type contact consisting of six fingers protected by an arcing ring. The moving contact is formed by a hollow contact rod the end of which is protected by an arcing ring of tungsten.
The extinction chamber consists of a heavy tube of insulating material and contains ten circular baffles. During



Low Oil Content Breaker
Figure 23

interruption the contact rod (1) is pulled downward by a gear mechanism located in the center portion of the circuit breaker. The expanding gases that the arc formed are forced to exhaust through the upper contact (2). The pressure in the arcing chamber itself is determined by the orifice in the neck above the contacts and by volume of the pressure chamber in the upper part of the chamber. The gases then exhaust through an oil separator which prevents free oil from being thrown out of the breaker. The gases are exhausted upward and the rod moves downward into cool oil; consequently, good cooling is obtained. The cooling is assisted also by the baffles which prevent the oil from being displaced by the generated gas too rapidly and results in a very close contact between oil and the arc. Fresh cool oil is forced through the hollow contact rod by an oil pump which is actuated by the same mechanism that operates the breaker. This is desirable to enable the breaker to operate on low currents.

This breaker is built for 135 KV and 3,500,000 KVA ratings.

Air Blast Breaker

The basic parts of an air blast breaker are the compressed air storage tank, the blast valve controlling the escape of the blast from the tank, and the arcing chamber where arc extinction is effected.

One of the most important parts of the arcing chamber is the zone of restricted cross-section where the potential energy inherent in compressed air is converted into the kinetic energy of the arc-extinguishing blast.

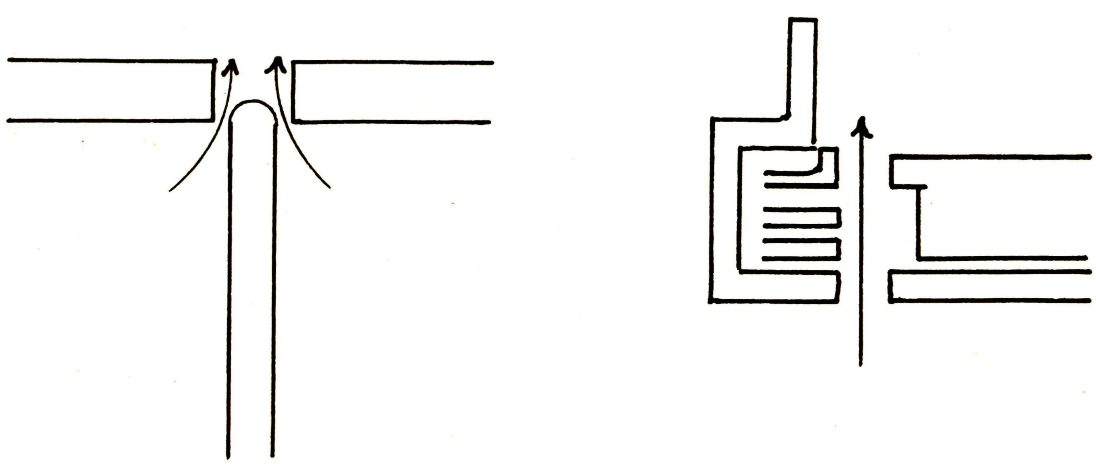
The laws of friction are different for below or equal to sonic velocity and those of super-sonic. Where flow velocity is low, the resistance is proportional to first power of the velocity. If the velocity is high, the resistance is proportional to the velocity squared. The change from the first power law to the second power law occurs in any given gas for any given structure always at the same critical velocity. If that velocity is exceeded, eddies are formed in which the gas motion is circular. Circular motion is one of the characteristics of turbulent gas flow. Turbulence occurring in the arcing chamber of the air blast breakers tends to increase the rate of deionization. The turbulence also has an unfavorable effect. It reduces the flow velocity wherever it occurs in the path of the blast.

Electrons and ions diffuse within a gas in the same way as gas molecules do. These electrons and ions are swept away by the blast. Air diffuses into the arc path replacing the charged particles.

An arc exposed to the action of an air blast assumes the position offering minimum drag by orienting itself in the direction of the blast. Its position then corresponds to that of a partition. It tends to reduce the blast velocity adjacent to the blast layer. The cross-section of the arc may be large enough to fill the arc chamber. Therefore, at a critical current the arc extinguishing blast may be completely stopped. The gas flow in the breaker may be reversed. As back pressure in the breaker recedes, the tank pressure may again force the flow of gas through the chamber.

The contacts of air blast breakers may be separated either in the direction of blast through the arcing chamber or transversely to that direction.

In the axial blast breaker, the blast approaches the arc gap radially through a circular opening and escapes from the gap axially in the opposite direction. This provides a cylindrical blast envelope that surrounds the entire surface of the arc. This is shown in Figure 24



Axial Blast Breaker Cross Blast Breaker

Figure 24

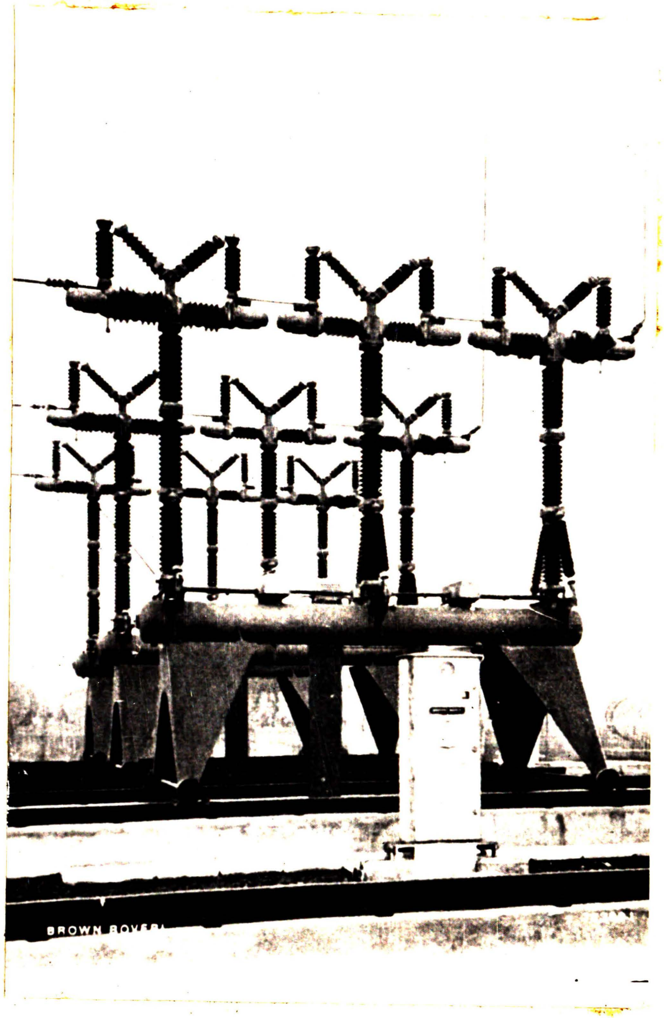
In the cross blast breaker the blast is across the arc gap forcing the arc down stream. Arc restraining barriers are located so that the arc is compelled to form loops around them. The down stream ends of the loops tend to float away with the blast. The ionized gas is rapidly replaced by non-ionized gas.

Interruption of high current arcs in an air blast breaker requires high tank pressures to overcome the back pressures.

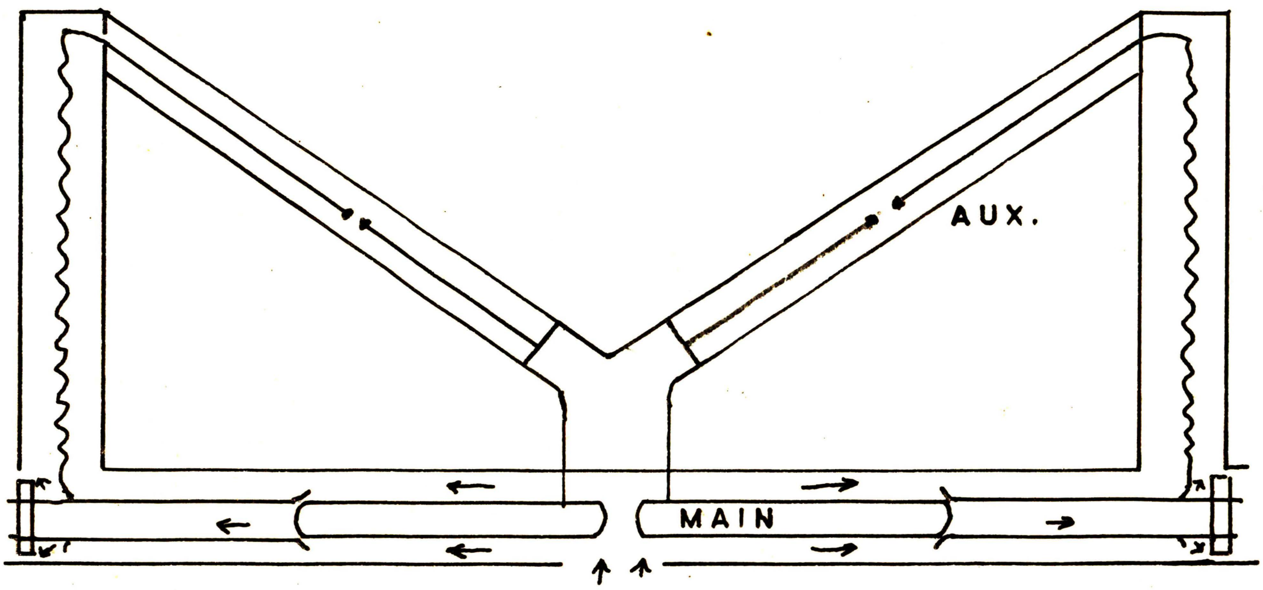
Low current arcs are more rapidly deionized than high current arcs because of the smaller amounts of ionized gas involved. The deionization is not limited to the surface of the arc core but takes place throughout the entire core space. This rapid interruption may give rise to high voltage surges which have already been discussed.

Air blast breakers have an inherent tendency to produce high restriking voltages and switching transients oweing to the short arcing time and quick recovery of the electric strength. The over voltages are produced by current chopping, when dealing with low currents. By proper design the breaker voltage is prevented from rising to a dangerous value by breaking down the gap. The deionizing agent is available in full at all values of current whereas the opposite is true in the oil breaker.

An example of the axial air blast breaker is the Brown Boveri outdoor blast breaker shown in Figure 25 on the next page.



Brown Boveri Air Blast Breaker



Contact Arrangement

Figure 25

The vertical insulator columns are hollow, so that they can conduct compressed air from the tank at the bottom of the structure to the arc extinction chambers. The main contacts and arcing chamber are housed in the horizontal insulator. The insulators above the arc extinction chamber, forming a letter "M" over each column, contain resistors and auxiliary breaks.

The breaker is operated by supplying compressed air through the insulator columns to the arc extinction chambers. When the air is supplied to the chambers, the auxiliary contacts which were normally open close very rapidly. This connects the resistors in parallel with the main breaks when they begin to open and during the whole arc extinguishing period. After arc extinction the auxiliary contacts part and the exhaust valves to the chambers close so that the open contacts are under compressed air. To reclose the breaker the column is vented by the main valve. When there is no compressed air in the chambers, the contacts are kept closed by strong springs.

During the arc extinguishing period the resistors are connected in parallel with the main breaks and bring about a practically uniform voltage distribution over the different arc extinction chambers. This results in higher capacity and in addition the resistors are capable of damping and limiting switching surges.

It is interesting to note from line dropping tests that the interrupting time varied between 1.97 and 2.39 cycles. Also due to the fact that no restrikes occurred the recovery voltage on the line never exceeded the normal phase-to-ground voltage of the line.

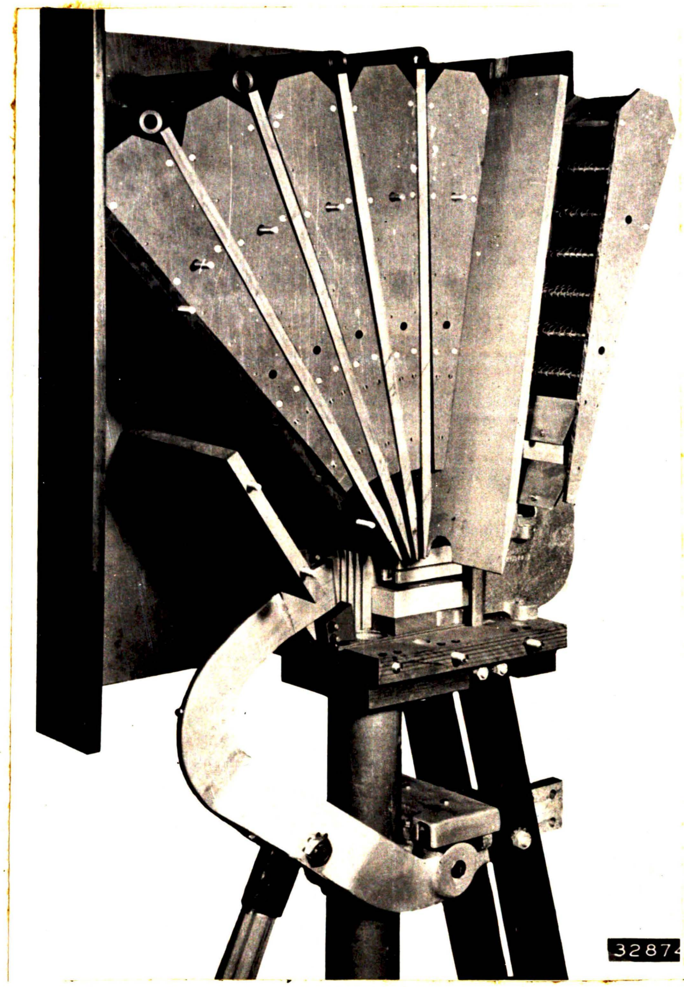
The breaker tested well above its rated capacity of 6,000,000 KVA symmetrical and 9,000,000 KVA asymmetrical. The interrupting time was always well below 3 cycles.

Another example of the compressed air breaker is the Westinghouse Cross-blast Air Breaker shown in Figure 26 on the next page.

The flow of air for arc interruption is in a straight line from the reservoir through arc chutes and mufflers to reduce pressure losses and insure maximum pressure in the contact gaps for arc interruption. Both opening and interruption are accomplished by compressed air.

The arc chute is a fiber lined "micarta" box, narrow at the base and widening toward the top. A number of fiber splitter plates within the chute converge near the base. The splitter plates have slotted bases with air spaces between them, and the arcing contacts move in the space formed by these slots. The arc is forced by the air blast against the splitters plates where interruption takes place.

The hot ionized gases are carried through a cooler assembly placed between the splitters before entering the muffler located above. The coolers consists of a series of metal screens graduating from coarse near the base to fine at the top to cool the arc gases as they pass through.



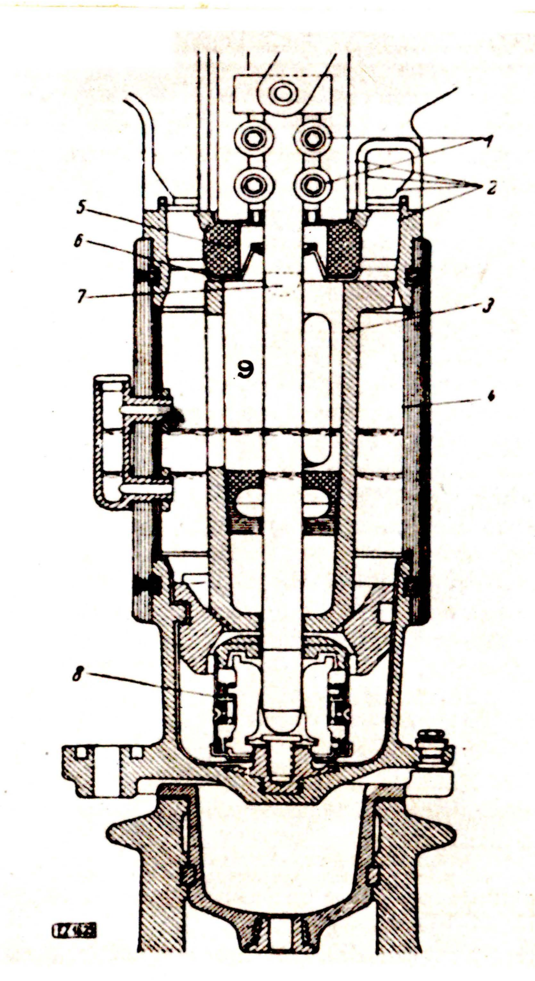
Westinghouse Cross-blast Air Breaker

Figure 26

Water Breaker

Many types of breakers have been developed to lessen the so-called fire hazard and eliminate the use of oil which is scarce in some countries. To meet these requirements the water breaker was developed. As the contacts part under water, high pressure is built up in a chamber for this purpose. This pressure forces a high pressure stream of steam and water out of the arc chamber. The arc is cooled by means of turbulence, convection, and expansion. The steam and water can be used as a blast to sweep away the arc products.

An example of this type of breaker is the Siemens Water Breaker shown in Figure 27.



Siemens Water Breaker
Figure 27

The moving contact is a rod type of contact and is raised out of the water through sets of roller contacts (1). The open position is indicated as (7) in the figure. The stationary contact is a tulip type of contact (8). As the moving contact is raised an arc is struck between the moving and stationary contacts. This arc is confined in the arc chamber (9). As the moving contact clears the opening in the arc chamber, a high pressure stream of steam which was generated by the arc follows the contact. This action sweeps the arc products out of that region. The steam upon reaching the chamber (3) expands. In this region the arc column is cooled. The steam condenses in the expansion chamber and upper passages. The chamber is vented to the outside at the top of the chamber. It is noted that the arc and expansion chambers are mounted with an elastic ring at the top (5). This gives an expansion mounting so that if extreme pressure is built up in the region of the stationary contact, the explosion chamber is raised to allow the pressure to escape.

The voltage rating of this breaker is 34.5 KV and 1,500,000 KVA.

SUMMARY

This thesis has presented the methods and techniques of modern circuit interruption. It is noted that a breaker which is designed for high voltages is not necessarily good for high currents but in actual practice these do not always go hand in hand. Also breakers that are designed for short circuit currents are not always the best or even suited for low current operations. There must be applications as near the breaker design as possible for best results.

In the next few years we can expect many more advancements in both power systems and their control.

APPENDIX

Appendix I

TABLE I

Breaker Duties for Symmetrical and Asymmetrical Currents Obtained from the Same Circuit Connections.(7)

rms Sym.	Int. Currents Asym.	e_r Recovery Volts	Actual Breaker Duty Compared to Duty for Sym.
1.0	1.4	0.63	0.88
1.0	1.3	0.80	1.04
1.0	1.2	0.88	1.06
1.0	1.1	0.96	1.06
1.0	1.0	1.00	1.00

TABLE II

Comparison of Application of Breakers Rated on Symmetrical Basis with ASA Asymmetrical Method.(7)

Total rms Current at Contact Parting Per Unit of Initial Current	Required Interrupting Capacity			Momentary Current Capacity Provided by Breakers	
	Present Rating Method	Sym. Rating	Momentary Duty	Present Rating Method	Sym. Rating
1.4	1.4	1.0	1.6	2.24	1.6
1.3	1.3	1.0	1.6	2.08	1.6
1.2	1.2	1.0	1.6	1.92	1.6
1.1	1.1	1.0	1.6	1.76	1.6
1.0	1.0	1.0	1.6	1.6	1.6

(7) Evans, Byron and Kilgore, C.L., Consideration in Testing, Rating, and Application of Power Circuit Breakers, AIEE 52-11, November, 1951.

TABLE III

Rated Voltages and Insulation Test Voltages

American			British		
Rated Voltage KV	Insulation Test		Rated Voltage KV	Insulation Test	
	60 Cy. KV	Impulse KV		50 Cy. KV	Impulse KV
4.16	19	60	3.3	9.44	None Specified
7.2	26	75	6.6	16.8	
13.8	36	95	11	26.8	
14.4	50	110			
23	60	150	22	51.5	
34.5	80	200	33	76.3	
46	105	250	44	101	
69	160	350	66	150.5	
			88	200	
115	260	550	110	250	
138	310	650	132	299	
161	365	750	165	374	
230	485	1050	220	497	
230*	425*	900*			

* The insulation level may be dropped to this level when system is effectively grounded as defined in American Institute of Electrical Engineers Standard No. 32 May 1, 1947.

TABLE IV

Permissable Temperature Rises When
Carrying Rated Normal Current

	American	British
		Continuous Ratings only. Higher values in some cases for intermittent service.
Frequency of Rated Current	60cps	50cps
Ambient	40°C #	40°C Peak Average for 24 hrs. 35°C
Contacts in air when clean and bright.	30°C	
Contacts in oil	30°C	
Any current carrying part having a rated current of 200 amperes or less.		30°C
For rated currents above 200 amperes and not above 800 amperes.		40°C
For rated currents above 800 amperes.		50°C
Oil	30°C	
Potential Coils Class O Insulation	35°C	40°C
Series Coils Class O Insulation	50°C	40°C
Series or Potential Coils Class A Insulation	50°C	50°C*
Series or Potential Coils Bare or Class B Insulation	70°C	85°C*
All other parts	70°C	Not Specified

* 40°C if oil immersed.

American circuit breakers installed in enclosures may be operated with an ambient of 55°C if the contacts are silver surfaced or equivalent and other related conditions specified in C-37.4 # 4-21b are met.

TABLE V

Rated Making and Rated Latching Currents #

Rated Voltage KV	Interrupting Capacity MVA	American Making Current Amperes	American Latching Current Amperes	British Making Current Amperes*
3.3	25			6,600
4.16	25	10,000	6,300	
3.3	50			13,200
4.16	50	20,000	12,500	
6.6	100			13,200
7.2	100	40,000	25,000	
11	150			11,820
13.8	150	35,000	22,000	
11	250			19,700
13.8	250	60,000	36,000	
11	500			39,500
13.8	500	70,000	44,000	
14.4	500	70,000	44,000	
11	750			59,000
14.4	2500	190,000	120,000	
33	1500			39,800
34.5	1500	61,000	38,000	
34.5	2500	96,000	60,000	
44	1500			29,800
46	1500	35,000	22,000	
66	1000			13,200
69	1000	16,000	9,600	
66	1500			19,700
69	1500	23,000	14,500	
66	2500			32,900
69	2500	38,000	24,000	
69	3500	53,000	33,000	

TABLE V (Cont.)

Rated Voltage KV	Interrupting Capacity MVA	American Making Current Amperes	American Latching Current Amperes	British Making Current Amperes*
132	1500			9,870
138	1500	11,500	7,200	
132	2500			16,300
138	5000	38,500	24,000	
220	2500			9,900
230	5000	21,000	13,000	

* These are rms amperes. The British Making Current is given in peak amperes and is the only current so measured. For convenience in comparison with the American Making Current and all other American and British ratings its equivalent rms value is used in this paper.

In most cases the American breaker is rated at the same MVA as the breaker with which it is grouped and can operate at full MVA to lower voltages. In some cases the maximum interrupting ratings at a service voltage are grouped to emphasize the magnitude of the currents which can be handled at these voltages even though no direct comparison of breakers can be made. Other ratings which are not directly comparable are not listed.

TABLE VI

Short Circuit Current Carrying Ratings

Rated Voltage KV	Interrupting Rating MVA	American Momentary Amperes	American 4 Second Amperes	British 1 Second Amperes
3.3	50*			8,760
	250			43,800
4.16	50	20,000	12,500	
6.6	100			8,760
	500			43,800
7.2	100	40,000	25,000	
11	150			7,880
13.8	150	35,000	22,000	
11	250			13,100
13.8	250	60,000	36,000	
11	500			26,300
13.8	500	70,000	44,000	
14.4	500	70,000	44,000	
11	750			39,400
14.4	2500	190,000	120,000	
22	1500			39,400
23	500	38,000	24,000	
33	1500			26,300
34.5	1500	61,000	38,000	
	2500	96,000	60,000	
44	1500			19,700
46	1500	35,000	22,000	
66	1000			8,760
69	1000	16,000	9,600	
66	1500			13,100
69	1500		14,500	
66	2500			21,900
69	2500	38,000	24,000	
	3500	53,000	33,000	

TABLE VI (Cont.)

Rated Voltage KV	Interrupting Rating MVA	American Momentary Amperes	American 4 Second Amperes	British 1 Second Amperes
132	1500			6,570
138	1500	11,500	7,200	
132	2500			10,900
138	5000	38,500	24,000	
220	1500			3,940
220	2500			6,570
230	3500	15,000	9,200	
230	5000	21,000	13,000	

* At each voltage class corresponding ratings are grouped and at some voltages the maximum ratings also are given. Other ratings which are not directly comparable are not listed.

TABLE VII

R/X (60 cycles)	D-C Component at End of 4 Cycles Times Initial D-C Component
.01	.78
.02	.61
.03	.47
.05	.28
.10	.08
.15	.02

TABLE VIII

Time after Start of Short Circuit Current in Cycles	Ratio: $\frac{\text{RMS Current}}{\text{RMS Value of Initial A-C Component}}$
1/2	1.6
1	1.4
2	1.2
3	1.1
4	1.0

TABLE IX

Time after Start of Short Circuit in Cycles	Ratio: $\frac{\text{RMS Current}}{\text{RMS of Initial A-C}}$
1/2	1.6
1	1.5
2	1.3
3	1.2
4	1.1

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